THE EMISSIONS FROM DIESEL POWERED TRAINS, AND THEIR IMPACTS ON AIR QUALITY IN RAILWAY DEPOTS AND STATION AND THE ROLE OF BIOFUELS

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Abstract

Concerns from the train company, Northern Rail regarding worker health & safety from diesel engine exhaust emissions (DEEE) led to the formation of this PhD project to investigate whether the extraction systems in place at their railway depot facilities are adequate to extract the DEEE from the depot. The aim of this project is to investigate the emissions of a portion of Northern Rail's fleet of diesel trains and to quantify their impact on air quality, whilst also looking at the potential for biofuels such as Hydrogenated Vegetable Oil (HVO) in current passenger rail use. The project will encompass four railway depot locations (Allerton, Heaton, Newton Heath and Neville Hill) and one train station (Manchester Victoria). Notable work has involved using diffusion tubes in parallel with Tinytag temperature devices to determine the vertical mixing profile in the repair shed of the Leeds depot. Data gathered from the repair shed section showed an increase in monthly, averaged, indoor temperature with height in tandem with increasing NO_2 monthly average concentrations with increasing height, over an approximate one year monitoring period between Apr 2018 and May 2019. This indicated that the repair shed is not well-mixed, inhibiting the effectiveness of the shed's fan based ventilation, which is likely to be operating below the estimated 6 ACH ventilation extraction rate. This trend in increasing pollutant concentration with height was also observed at the main shed of each of the other 3 railway depots of Allerton, Heaton and Newton Heath, in addition to the Manchester Victoria train station, thereby providing evidence of a concentration gradient at each of these locations.

All of these location are compliant to HSE EH40 workplace exposure limits, however, the concentrations of NO_2 with 4 out of 5 locations based on diffusion tube measurements, having annualised NO_2 concentrations above the UK air quality standard for NO_2 of 40 µg m^{-3}. Respectively these locations are the Heaton railway depot (99 µg m^{-3}), Neville Hill railway depot (57 µg m^{-3}), Newton Heath railway depot (48 µg m^{-3}) and the Manchester Victoria train station (54 µg m^{-3}). Alternative fuels, such as GTL (Gas to Liquids) and HVO (Hydrogenated Vegetable Oil) are one such way to both improve air quality at source, and decarbonise the WTW pathway for the fuel used in diesel rail vehicles. GTL demonstrated WTW NO_x reduction of 6% vs red diesel, with HVO demonstrating a similar WTW NO_x reduction of 5% vs. red diesel. For PM_{10}, GTL showed a WTW PM_{10} reduction of 27% and UCO (used cooking oil) HVO showed a 42% WTW reduction. For GHG, GTL only resulted in 9% GHG reduction whereas HVO resulted in 91% reduction in GHG vs. red diesel.

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a	stoichiometric coefficient of CO
A	Area
ACH	Air Changes per Hour
ADCU	Ammonia dosing control unit
AEF	Aviation Environment Federation
A-F	Air fuel
AQEG	Air Quality Expert Group
AQMA	Air Quality Management Area
AQMN	Air Quality Monitoring Network
AQS	Air Quality Standard
ASDS	Ammonia Storage & Delivery System
ASTM	American Society for Testing and Materials
ATQ	Arriva Trains Wales
AU	Australia
AURN	Automatic Urban and Rural Monitoring Network
Av.	Average
B100	100% Biodiesel
BAM	Beta Attenuation Monitoring
BEIS	Department of Business, Energy and Industrial Strategy
BC	Black Carbon
BDC	Bottom Dead Centre
BS	British Standard
BSN	Bosch Smoke Number
BTDC	Before Top Dead Centre
BTEX	Benzene, Toluene, Ethylbenzene and Xylenes
CA	Crank Angle
Ce	Elemental Carbon
CF_b	Relative national bias correction factor
CF_l	Relative local bias correction factor
CC	Cross Country
$[NO_2]$	Ambient Concentration of NO_2
$C_nH_{2n+1}O$	Alcohol General Formula
CAER	Cycle Average Emission Rate
CH_4	Methane
CHAN	Chemical Hazard Alert Notices
CIBSE	Charted Institution of Building Service Engineers
CI	Compression Ignition
CLA	Chemiluminescence Analyser
CLD	Chemiluminescence Detector
Co	Average consumption in kWh km^{-1} per 150 DMU
CO	Carbon Monoxide
CO_2-e	Carbon dioxide equivalent
COSHH	Control of Substances Hazardous to Health
COMEAP	Committee on the Medical Effects of Air Pollutants
CPC	Condensation Particle Counter
CSA	Cross Sectional Area of fan
Cu	Copper
CVS	Constant Volume Sampling
d	Annual distance in km travelled by the entire 150 DMU fleet of Northern Rail
D	Depth
D_{12}	Diffusion coefficient
D_p	Diameter of a particle
$\frac{dC_{NO_2}}{dt}$	Rate of accumulation of NO_2
DC	Direct Current

DEEE	Diesel Engine Exhaust Emission
DEFRA	Department for Environment, Food and Rural Affairs
DfT	Department for Transport
DI	Direct Injection
DMU	Diesel Multiple Unit
DMS	Driving Motor Second
DMSL	Driving Motor Second Lavatory
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
E	Emission rate
EA	Annual energy use of the entire 150 DMU fleet of Northern Rail
EI_x	Emission index of pollutant x
EC	Elemental Carbon
ECU	Engine control unit
ELPI	Electrical Low Pressure Impactor
EGR	Exhaust Gas Recirculation
EGT	Exhaust Gas Temperature
EMR	East Midlands Railway
eqn.	Equation
ESG	Environmental Scientific Group Ltd.
EU	European Union
fCh_{NOx}	The fractional change in exhaust NOx emissions between low sulphur diesel and an alternative fuel
fCh_{PM10}	The fractional change in exhaust PM_{10} emissions between low sulphur diesel and an alternative fuel
fCh_{GHG}	The fractional change in exhaust GHG emissions between low sulphur diesel and an alternative fuel
FAME	Fatty Acid Methyl Ester
FDMS	Filter Dynamics Measurement System
FID	Flame Ionisation Detector
FGW	First Great Western
FTIR	Fourier Transform Infrared
GHG	Greenhouse Gases
GMCA	Greater Manchester Combined Authority
GTL	Gas to Liquids
GWR	Great Western Railway
h	height
H	Monatomic Hydrogen
HC	Hydrocarbons
HEPA	High Efficiency Particulate Air
HGV	Heavy Goods Vehicles
HP	Horsepower
hr	Hour
HSE	Health and Safety Executive
HSL	Health and Safety Laboratory
hv	Energy of wavelength
HVO	Hydrogenated Vegetable Oil
IDI	Indirect Injection
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
JRC	Joint Research Council
l	Length of the diffusion tube
L	Length
LAQM	Local Air Quality Management
LCA	Life cycle analysis
LCC	Leeds City Council
LICC	Liverpool City Council

LDL	Lowest Detection Limit
LEV	Local Extraction Ventilation
LNER	London North Eastern Railway
K	Ratio of the molecular weight of species x divided by the molecular weight of air
M	Third body species
m_i	mass emission rate of a given pollutant i
Me	Methanol
M_W	Molecular Weight
MCERTS	Monitoring Certification Scheme
min	Minute
MON	Motor Octane Number
ms	Millisecond
n	Number
NAEI	National Atmospheric Emissions Inventory
NAQO	National Air Quality Objectives
NCC	Newcastle City Council
NDIR	Non-Dispersive Infrared
NEPC	National Environment Protection Council
NES	National Environment Standard
NIOSH	National Institute for Occupational Safety and Health
NZ	New Zealand
N_{DMU}	Total number of 150 DMUs in use by Northern Rail.
N150	Number of 150 carriages
N155	Number of 155 carriages
N158	Number of 158 carriages
N170	Number of 170 carriages
NH_3	Ammonia
NO	Nitrogen Oxide/Nitric Oxide
NO_x	Nitrogen Oxides
NO_2	Nitrogen Dioxide
N_2O	Nitrous Oxide
NZ	New Zealand
O	Monatomic Oxygen
O_3	Ozone
OC	Organic Carbon
OEL	Occupational Exposure Limit
ON	Octane Number
OS	Ordnance Survey
OSHA	Occupational Safety and Health Administration
P	Pressure
PAH	Polycyclic Aromatic Hydrocarbon
PAN	Peroxyacetyl Nitrate
PE	Polyethylene
PEL	Permitted Exposure Limit
PEMS	Portable Emissions Measuring System
PM	Particulate Matter
PN	Particle Number
POC	Primary Organic Carbon
PTFE	Polytetrafluoroethylene
PW	Power
q_e	Exhaust volumetric flow rate
$\overline{q_{e,n}}$	Average exhaust volumetric rate for a given notch
q_{NO_2}	Source emission rate of NO_2 in mg min^{-1}
R	Radical (Alkane)
RC	Railcar

RC A	Railcar for Stage IIIa
RD	Respirable Dust
RDG	Rail Delivery Group
R B	Rail locomotive for Stage IIIIB
RH A	Rail locomotive for Stage IIIA above 560 kW
RL	Rail locomotive
RL A	Rail locomotive for Stage IIIA between 130-560 kW
RLL	Rail locomotives of any power rating or ignition type
RLR	Railcars of any power rating or ignition type
REP	Recommended Exposure Period
ROSCO	Rolling Stock Operating Company
RON	Research Octane Number
rpm	revolutions per minute
RSSB	Rail Safety and Standards Board
SAF	Sustainable aviation fuel
SCR	Selective Catalytic Reduction
SCOEL	Scientific Committee on Occupational Exposure Limit Values of the European Commission
SD	Stack Diameter
SFD	Sulphur Free Diesel
SMPS	Scanning Mobility Particle Sizer spectrometer
SOC	Start of Combustion
SI	Spark Ignition
SOI	Start of Injection
SO_2	Sulphur Dioxide
STEL	Short Term Exposure Limit
SWR	South Western Railway
SWT	South West Trains
t_i	Duration of the measurement for pollutant X
T	Temperature
TDC	Top Dead Centre
THC	Total Hydrocarbons
TQ	Torque
T_a	Ambient temperature
T_e	Indoor, ground level temperature
$T_{e,\ 1min\text{-}av}$	Indoor, 1 min-averaged temperature
$T_{e,\ 3min\text{-}av}$	Indoor, 3 min-averaged temperature
T_i	Indoor temperature
TEA	Triethanolamine
TEOM	Tapered Element Oscillating Microbalance
THC	Total Hydrocarbons
TOC	Train Operating Company
TLV	Threshold Limit Value
TPE	Transpenine Express
TRGS	Technical Rules for Hazardous Substances
$TTW_{alternative\ fuel,NOx}$	Tank-to-Wheel distance based NO_x emission factor of alternative fuels for a given species
$TTW_{diesel,NOx}$	Tank-to-Wheel distance based NO_x emission factor of low sulphur diesel fuel for a given species
$TTW_{alternative\ fuel,PM10}(g\ pkm^{-1})$	Tank-to-Wheel distance based PM_{10} emission factor of alternative fuels for a given species
$TTW_{diesel,PM10}(g\ pkm^{-1})$	Tank-to-Wheel distance based PM_{10} emission factor of low sulphur diesel fuel for a given species
$TTW_{alternative\ fuel,GHG}(g\ pkm^{-1})$	Tank-to-Wheel distance based GHG emission factor of alternative fuels for a given species
$TTW_{diesel,GHG}(g\ pkm^{-1})$	Tank-to-Wheel distance based GHG emission factor of low sulphur diesel fuel for a given species
TWA	Time Weighted Average

TfW	Transport for Wales
u	Wind speed
UHC	Unburnt hydrocarbons
UIC	Union Internationale des Chemins de fer
ULSD	Ultra-Low Sulphur Diesel
UK	United Kingdom
US	United States of America
v	Speed
V	Volume
V_e	Extraction volume
V_s	Volume of the shed
VCC	Virgin Cross Country
VOC	Volatile Organic Compound
W	Width
WEL	Workplace Exposure Limit
WES	Workplace Exposure Standard
WHO	World Health Organisation
WHTC	World Harmonised Transient Cycle
wt.	Weight
WTW	Well to Wheel
x	number of moles of Carbon from reaction balance for equation 2.9
x_1	regression equation coefficient for variable 1
x-a	stoichiometric coefficient of CO_2
XS_t	Cross sectional area of tube
yr	year
$[c]_i$ (in ppm)	average concentration for a given pollutant i in ppm
$[c]_i$ (in vol%)	average concentration for a given pollutant i in vol%
[BD1]	Bias corrected annualised mean period concentration
[d]	Diffusion tube concentration
$[NO_2]_t$	Concentration of NO_2 introduced at a constant rate into a ventilation space of volume at time t
$[NO_2]_{t+1}$	Concentration of NO_2 introduced at a constant rate into a fixed volume at time t+1
$[NO_2]^-$	Nitrite concentration
$[NO_2]_{293K}$	Concentration of NO_2 at 293K
$[NO_{2,\ h\text{-}av,}]$	Indoor, ground level hourly-averaged NO_2 concentration
$[NO_{2,\ 8\ h\ TWA}]$	8h TWA NO_2 concentration
$[NO_{2,\ min}])$	Maximum, indoor ground level concentration of NO_2
$[NO_{2,\ max}]$	Maximum, indoor ground level concentration of NO_2
$[NO_{x,\ 3min\text{-}av}]$	Indoor ground level, 3 min-averaged NO_x
$[NO_2]_b$	Background concentration
[NO]	Concentration of NO
[NOx]	Concentration of NOx
$[NO_2]$	Concentration of NO_2
$[PM_{2.5}]$	Concentration of $PM_{2.5}$
$[PM_{2.5,\ 1min\text{-}av,}]$	Indoor, ground level, 1 min-averaged $PM_{2.5}$ concentration
$[PM_{2.5,\ max,}]$	Maximum, indoor ground level concentration of $PM_{2.5}$
$[PM_{2.5,\ h\text{-}av,}]$	Indoor, ground level hourly-averaged $PM_{2.5}$ concentration
[STEL]	Time weighted average (15 min) for a particular pollutant X in mg m^{-3} or ppm
[TWA]	Time weighted average (8 h) for a particular pollutant X in mg m^{-3} or pp
$[X]_i$	Exposure or concentration of X at duration i in mg m^{-3} or ppm
[X](in ppm)	Concentration of a given pollutant X in ppm
[X](in vol%)	Exhaust concentration of a given pollutant X in %vol
ΔH	rise of the plume above the stack

ΔT_s	stack gas temperature minus the ambient air temperature
ΔX	change in exhaust concentration uncertainty
ΔY	change in volumetric flow rate uncertainty
ΔZ	change in mass flow rate uncertainty
$\sum_1^n [X]_i$	sum of concentration X from time period i to n
∝	air exchange rate in h^{-1}
ρ_E	exhaust density
σ	standard deviation
τ	Residence time
µm	micrometre
µs	Microseconds
°	Degree
%m/m	% Mass in solution
%vol	%volume percent
0.5y	stoichiometric coefficient of hydrogen for equation 2.9

Chapter 1 Introduction

The UK's diesel trains are subdivided into three categories, diesel multiple unit (DMU) trains, diesel locomotive trains and bi-mode diesel-electric trains. In DMU trains, each train carriage has a designated engine, and these are coupled together in sequence, of either 2, 3, 4, 6 or 8 carriages in series. Locomotives on the other hand, have a single driving engine at the front end of the train coupled to a series of carriages without engines. This locomotive engine is used to drive movement in the other carriages. The third category of diesel trains, bi-mode diesel-electric trains, have two power options, where the rail line is electrified, the train is powered by electric power via pantograph connected to overhead electric lines, where the rail line is not electrified, an on-board diesel engine is activated and is used to power the train.

In the UK, DMU trains comprise approximately 30% of the total UK passenger fleet, and 80% of the diesel passenger trains (DMU 30%, 6% Bi-mode, 2% Diesel locomotive) in the UK (DfT, 2021e), and are of interest to this project. Many of these DMU trains contain engines without any exhaust aftertreatment technology, and in some cases were manufactured as far back as 1985 (DfT, 2018; Ian, 2006b). These pre-1990 DMU vehicles emit a significant amount of nitrogen oxides (NO_x = $NO+NO_2$) due to an absence of a deNO_x system to scrub out the NO_x generated in the engine exhaust. As a result, DMU trains can potentially have a negative effect on air quality, as a consequence of unmitigated emission sources associated with the DMUs.

Poor air quality whether indoors or outdoors can have adverse effects on human health, ranging from breathing difficulties in the short term to reduced lung function with long term exposure (WHO, 2018; WHO, 2021b). NO_2 (nitrogen dioxide) and PM (particulate matter) are the main pollutants which result in a degradation of air quality. NO_2 is a gaseous pollutant formed from multiple sources, including fuel engine combustion but can also form from atmospheric interactions between O_3 (ozone) and NO (nitric oxide) (Sher, 1998b). NO_2 negatively impacts the lungs by inflaming their lining, in addition to weakening the immune system to lung infections over the long term (AQEG, 2004). PM_{10} is defined by AQEG (Air Quality Expert Group) as "airborne particulate matter passing a sampling inlet with a 50% efficiency cut-off at 10 µm aerodynamic diameter and which transmits particles of below this size" (DEFRA). $PM_{2.5}$ is defined a "airborne particulate matter passing a sampling inlet with a 50% efficiency cut-off at 2.5 µm aerodynamic diameter and which transmits particles of below this size" (DEFRA). Air pollutants, such as NO_2, $PM_{2.5}$

and PM_{10} are present with the diesel engine exhaust emissions (DEEE) of UK train DMUs, and the impact of DMUs on air quality are of interest to this project. This is because, with poor ventilation to remove the DEEE, rail workers and in certain exposure environments, passengers, can be exposed to these air pollutants and suffer negative health effects, as noted previously.

1.1 Legal framework for air quality monitoring and compliance within the UK

The UK has certain limits for ambient concentrations of NO_2 and PM_{10}, known as air quality standards (AQS) outlined in the National Air Quality Objectives (NAQO) by DEFRA (Department for Environment, Food and Rural Affairs) as seen in Table 1.1 (DEFRA, 2007; EU, 2008a).

Table 1.1 National air quality objectives for the UK (DEFRA)

Pollutant	**NO_2**		**PM_{10}**		**$PM_{2.5}$**	
Concentration	**Hourly**	**Annual mean**	**24 hour mean**	**Annual mean**	**24 hour mean**	**Annual mean**
	200 µg m^{-3} not to be exceeded by more than 18 times in a calendar year	40 µg m^{-3}	50 µg m^{-3} not to be exceeded more than 35 times a year	40 µg m^{-3}	-	20 µg m^{-3}

The UK has a number of air quality management areas (AQMAs) declared on the basis of pollutants such as NO_2 and PM_{10}. AQMAs are areas which the local authorities within the UK, have identified as likely to fail the UK AQSs for a given pollutant. An AQMA can be “as small as one or two streets” or can cover large areas (DEFRA, 2018a). In Leeds, there are 4 AQMAs relatively nearby to the Neville Hill railway depot, as seen in Figure 1.1. These are: Ebor Gardens (East Leeds), Caspar Apartments (Central Leeds), The Normans (Kirkstall) and The Tilburys (Islington)

(DEFRA, 2017b). Neville Hill is the main passenger rail maintenance depot in Leeds, indicating a possible impact of emissions from maintenance work on DMUs to surrounding air quality. As such, Neville Hill, is a location of particular interest to this project. However, there is no AQMA specifically, where the Neville Hill railway depot is located. The nearest AQMA to the depot is situated in Ebor Gardens and is located on the junction between Burmantofts Street and the A64 York Road, which is approximately 1.5 miles west of the Osmondthorpe area and 1.8 miles from the Neville Hill railway depot.

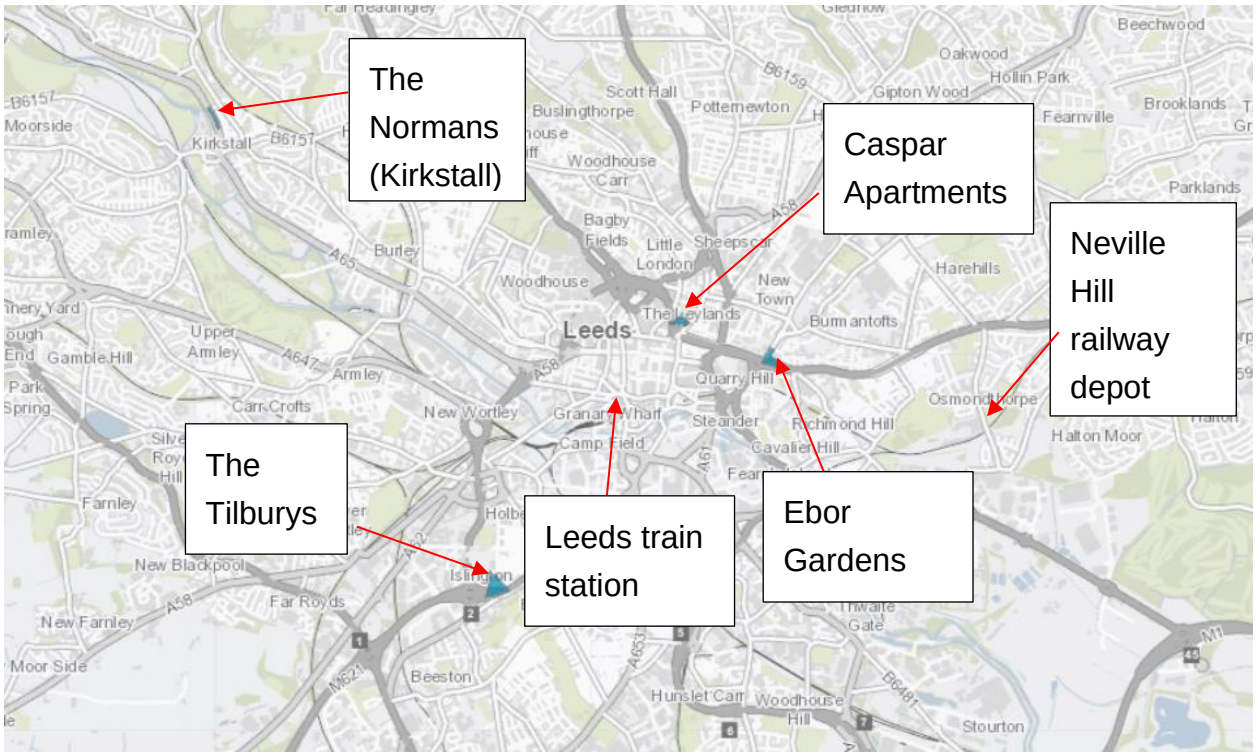

Figure 1.1 AQMAs in Leeds (DEFRA, 2017b). © Crown copyright and database rights 2022 licenced under DEFRAs Public Sector Mapping Agreement with Ordnance Survey (licence No. 100022861).

1.2 Legal framework for air quality in indoor settings

Within railway depots and train stations in the UK, the indoor air quality is regulated by the HSE (Health and Safety Executive), with each chemical having a workplace exposure limit (WEL) which is outlined within the HSE's EH40 standard (HSE, 2005d). These are set typically on 15 min and 8 h time weighted periods, with the 15 min period referred to as 15 min STEL (Short Term Exposure Limit) and the 8 h period, as 8 h TWA (Time Weight Average). The HSE EH40 WELs are designed to ensure a safe working environment.

For NO_2 , there are two HSE WELs 0.5 ppm at 8 h TWA and 1 ppm at 15 min STEL(HSE, 2007; SCOEL, 2014). which have adopted EU occupational exposure limits (OEL) recommendations through the SCOEL (Scientific Committee on Occupational Exposure Limit) body within SCOEL/SUM/53. It can be noted however, that when converting these NO_2 WELs into units of µg m^{-3} and comparing them against DEFRA's UK AQS for NO_2 as set out in the national air quality objectives, there is a substantial difference between the two standards. Using a conversion factor of 1.9125 from ppm to µg m^{-3} as per DEFRA guidance, the HSE NO_2 WELs, become 955 µg m^{-3} (0.5 ppm) at 8 h TWA and 1910 (1 ppm) µg m^{-3} at 15 min STEL (DEFRA, 2014; HSE, 2005d). These are much higher than DEFRA's AQS NO_2 hourly limit of 200 µg m^{-3} (with 35 allowable exceedances) and the annual AQS NO_2 limit of 40 µg m^{-3} as noted earlier in Table 1.1 (DEFRA). It must be noted that the timescales are different between the standards, with 15 min and 8 h periods used for the WELs, in contrast to hourly and annual periods for the DEFRA AQS. Also, it is key to note that only the HSE WELs have legal effect inside buildings such as railway depots whereas the DEFRA AQS are designed for outdoor and roadside environments and have no legal effect inside buildings.

In terms of PM, there are no dedicated $PM_{2.5}$ or PM_{10} WELs. Instead three de-facto measures are used for PM, firstly, Black Carbon (BC) a constituent of $PM_{2.5}$ which has an 8 h WEL of 3.5 mg m^{-3} and 15 min STEL of 7 mg m^{-3}. Secondly, Respirable Dust (RD) which has a COSHH (Control of Substances Hazardous to Health) advisory limit of 4 mg m^{-3} 8 h TWA (ORR, 2018a; HSE, 2005a). It must be noted that the respirable dust COSHH limit is not a WEL. Thirdly, Elemental Carbon (EC), a constituent of PM, is also used a de-facto measure, although it does not have a UK WEL, as codified within the HSE's EH40 limits, instead the HSE's uses an old version (~2014) of the German occupational exposure limits of TRGS900 of 0.1 mg m^{-3} 8 h TWA as a reference point for elemental carbon (ORR, 2014; ORR, 2018b). It must be noted the German TRGS900 no longer use 0.1 mg m^{-3} as their benchmark for elemental carbon, termed "Dieselmotoremissionen (Dieselrußpartikel, als EC (elementarer Kohlenstoff))" within TRGS900, which has a much stricter limit 0.05 mg m^{-3} 8 hr TWA for elemental carbon (Baua, 2022).

A list of both the short and long term exposure limits to be used as a benchmark for a number of species involved in this project for indoor air quality assessment are included in Table 1.2.

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Table 1.2 List of exposure limits for species involved in this project for benchmarking (Li, 2017; HSE, 2005c; Visser, 2014; NIOSH, 2005; HSE, 2005a; OHSA, 2018)

Species	HSE WEL		COSHH		
	8 h TWA		8 h TWA	15 min STEL	
	ppm	mg m^{-3}	mg m^{-3}	ppm	mg m^{-3}
NO	2	2.5			
NO_2	0.5	0.96		1	1.91
Respirable Dust			4		
Black Carbon		3.5			7
Elemental Carbon		0.1			

1.3 Potential emissions from the rail sector and relevance to occupational and passenger exposure.

Within the rail sector, there is a growing concern of indoor air quality, with poor air quality observed in the Birmingham New Street train station from a study in 2018, which required subsequent Network Rail intervention for improved diesel fume extraction within the station area (Jackson, 2018; IAQM, 2021; Thornes et al.; Hickman et al., 2018b); NO_2 and PM were the main pollutants of concern at the station. More recently, in 2020, a number of rail staff complaints were publically made to the BBC and the Yorkshire Post about diesel exhaust fumes from trains at the Neville Hill railway depot in Leeds; a depot which is also researched in this project. The complaints related however to the East Midlands Railway (EMR) section of the depot, which is outside of the remit of this project, within one of EMR's maintenance sheds. According to news reports, the fumes were described as a "toxic fog" (Boriboonsomsin et al., 2018; Newton, 2020). One possible reason for complaints about poor air quality in the rail sector is that the engines in many of the UK's diesel passenger trains have no aftertreatment systems, leading to a large amount of harmful pollutants such NO_2 and PM being released into confined railway depots and train stations during routine maintenance, and into the atmosphere

during passenger use. In so doing, this exposes both rail staff and passengers to NO_2 and PM, both of which have negative health effects, with coughing and wheezing in the short term, to potentially death in the long term, as tragically was the case with Ella Adoo-Kissi-Debrah (AQEG, 2004; EPA, 2020; AusGOV, 2005; BBC, 2021; Barlow, 2021) (ORR, 2020; Ogleby, 2018; Jackson, 2018; BBC, 2020; BBC, 2021; Newton, 2020).

Northern Rail, whose rail facilities are utilised for the remit of this project, have an interest in safe workplace exposure conditions for their staff working within their railway depots and stations, and are the primary drivers for this project. Northern Rail has identified 4 key railway depots and 1 train station (Figure 1.2) within the UK, for research in the area of indoor air quality. The four railway depots include Allerton in Liverpool, Newton Heath in Manchester, Neville Hill in Leeds and Heaton in Newcastle as well as one train station, i.e. Manchester Victoria station in Manchester city centre.

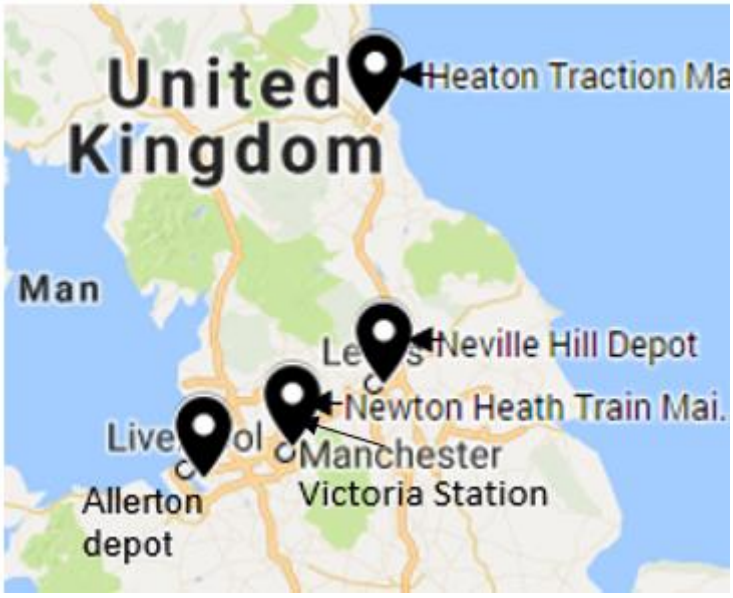


Figure 1.2 Map showing the 5 locations considered in this project (Google, 2022a)

These locations in particular are in confined environments with ceiling roof fans for extraction within the depots and overbridge areas interconnecting platforms with no ventilation at all within the Manchester Victoria station; although there is ducted ventilation above each individual platform at the station. In this project, both the indoor air quality and emissions at source will be measured at these locations, with NO_2 and $PM_{2.5}$ of particular interest as the primary air pollutants that often lead to the declaration of AQMAs within the UK. The changes in concentration with height for both these species, as well as indoor temperature, will be researched as part of this

work, in order to investigate the effectiveness of current extraction strategies for air pollutants within these locations. The analysis will be supported by predictive tools such as box models for the prediction of changes in pollutant concentrations.

1.4 Decarbonisation of rail fleet

Northern Rail, in addition, to minimising and controlling the pollution associated with their diesel fleet, in terms of air quality, also have a commitment to minimise the carbon emissions from their fleet (DfT, 2015). Carbon emissions, in the form of carbon dioxide (CO_2) contribute to global warming, as a greenhouse gas, with a consequential change in the global temperature. Increases in the global temperature to just 1.5°C above the pre-industrial reference period of 1850-1900, according to the IPCC (Intergovernmental Panel on Climate Change) is predicted to have a number of negative effects including 'warming of extreme temperature in many regions, increases in frequency, intensity, and/or amount of heavy precipitation in several regions' (IPCC, 2019) . To mitigate this, the UK Government has committed to reached net-zero by 2050 (DfT, 2021a). Net zero is when the greenhouse gas emissions (GHG) released into the atmosphere is sufficiently low to be balanced by the amount of greenhouse gases being removed from the atmosphere. In the UK, domestic transport contributes to 27% of greenhouse gases (GHG) of UK GHG emissions, based on 2019 data. Of this, rail only contributes to 1.4% of UK domestic transport GHG emissions. Whilst UK rail is relatively small contributor to GHG from UK transport, there are still areas in which the UK rail can decarbonise, which have been identified by the UK Government.

The UK Government, through the Department for Transport's (DfT) have outlined a strategy (Decarbonising Transport – A Better Greener Britain) to decarbonise the UK railway network.by aiming to 'deliver a net zero railway network by 2050' and 'remove all-diesel-only trains (passenger and freight) from the network by 2040' (DfT, 2021a). To support this, Northern Rail, as one of the passenger railway operators, have outlined an environment strategy, to assess and reduce their carbons emissions throughout their company's operations (Northern, 2022). This includes minimising the consumption of diesel fuel for rail operations and minimising the amount of natural gas used within its company operations. This research project, co-funded by Northern Rail, will further support Northern Rail's decarbonisation commitments, through the investigation of non-diesel, alternative fuels, as options for decarbonising Northern Rail's diesel fleet.

Using Well-to-Wheel (WTW) analysis, low-sulphur diesel from a typical non-aftertreatment diesel train (train class: 158) will be compared against the alternative fuels of GTL (Gas to Liquids) and HVO (Hydrogenated Vegetable Oil), to predict any potential reductions in the greenhouse gases emissions for these fuels. Interlinking with air quality, the same WTW analysis, can also be conducted for NO_x and PM_{10}, which are air pollutants of interest. This project will also use WTW analysis to observe any reductions in NO_x and PM_{10} with replacing diesel with either GTL or HVO, along the fuel life cycle from extraction to combustion.

1.5 Aims & objectives

This work aims to investigate the emissions of Northern Rail's fleet of DMU trains and to quantify their impact on air quality whilst also looking at the potentials of alternative fuels such as GTL and HVO in carbon and pollutant reductions within these same DMUs. The objectives of this project are:

O1. To determine the parameters that affect air quality within UK railway depots and train stations where diesel trains are in operation.

O2. To measure the emission levels of Northern trains in a working railway depot, and to compare this emission data against other vehicles.

O3. To assess the WTW impacts of introducing alternative fuels into diesel-powered trains.

1.6 Research Questions

Alongside the aims and objectives, four key research questions have been outlined to support this work:

R1: What are the emission levels of Northern Rail DMUs in a railway depot, and how do these emissions compare to other vehicles?

R2: What are the WTW life cycle impacts which need to be considered when introducing alternative fuels into diesel-powered trains?

R3: What factors need to be considered when introducing alternative fuels into diesel-powered trains?

R4: What type of parameters affect the air quality in UK railway depots and train stations where diesel trains are in operation?

Research question 1 will be discussed in Chapter 4 (section 4.2) on rail exhaust emission measurements. Research question 2 will be also discussed in Chapter 4 (section 4.3) covering the WTW life cycle impacts of utilising alternative fuels. Research question 3 will also be discussed in Chapter 4 (section 4.4) covering the current UK policy towards alternative fuels in rail and factors which may affect a switch from diesel to alternative fuels in rail. Research question 4 will be discussed in Chapters 5 and 6, which cover the box model, the NO_2 diffusion tube data for the 4 railway depots, transient NO_x/$PM_{2.5}$ measurements in the repair shed of the Neville Hill railway depot and the Manchester Victoria NO_2 diffusion tube data respectively.

This project aligns with wider work by the RSSB (Rail Safety & Standards Board) in rail air quality research and supports the rail air quality improvement ambitions of the UK Clean Air Strategy 2019 (RSSB, 2020; DEFRA, 2019). The RSSB's work, in the case of railway depots (RSSB project T1190) in conjunction with Hilson Moran, took place towards the end of this project, and looked at the effect of pollution originating from 6 depots, (one of which was the Neville Hill railway depot) on nearby areas, typically residential areas (RSSB, 2021b). The T1190 report concluded that the railway depots considered in their study had a "relatively limited impact on pollutant concentrations beyond the depot boundary" (RSSB, 2021b). In the case of stations, the RSSB T1122 project evaluated the indoor air quality within two train stations, Edinburgh Waverley and King's Cross, in conjunction with the University of Edinburgh and King's College London (RSSB, 2019; Font et al., 2020). Detailed statistical modelling through the random forests method attributed the indoor air pollution to specific trains within each of the stations in the T1122 report.

The originality of the project can be justified by no prior research work having considered vertical air quality measurements within the rail sector. Similar projects, however, have been carried out in both rail air quality and rail exhaust emission testing and data from these projects will be used to support this research. Birmingham University investigated the indoor and outdoor air quality at Birmingham New Street Station and the surrounding areas outside of the station. Data from this previous research will be used as a comparison point for the air quality data gathered in this study, and to support research question 4 (Hickman et al., 2018a). In addition, there has been work carried out by the RSSB in 2006 to determine the emission rates in g/kWh of a selection of Cummins and Perkins engines utilised within DMU trains (Ian, 2006b). Northern Rail utilise many of the same Cummins engines investigated by the RSSB within their leased train fleet, so there is reference data from the RSSB study to compare this project's emission rates against, and this will be support research question 1.

1.7 Thesis structure

The thesis is organised into the following sections:

Chapter 1 provides an introduction to the project, with details on the background of the project in the rail sector, outlining the test locations for air quality monitoring within indoor rail maintenance depot environments, setting out the aims, objectives and 4 research questions for the project, as well as outlining the thesis structure.

Chapter 2 examines current literature, including applicable legislation and previous studies conducted in primarily rail environments with datasets from a number of UK train stations including London Paddington, Birmingham New Street, London King's Cross and Edinburgh Waverly. Roadside data from a network of 7 continuous automatic monitoring sites together with 2 AURN (Automatic and Urban Rural Network) monitors in Leeds are also included for comparison against the Leeds Neville Hill railway depot site considered in this work. In terms of emission data, a review of rail emission testing in the UK has been conducted. There is a short review of previous work on indoor temperature gradients. This chapter outlines the gaps in the research that this project is aiming to fill.

Chapter 3 outlines the methodology used to evaluate air quality within 4 railway depots and 1 train station. Specifications of the 4 railway depots under consideration for this study are detailed, including the trains present across the 4 railway depots. The test procedure for exhaust emission measurement and ambient air quality monitoring is defined for the pollutants under consideration. A plan for the box model is outlined, in which the purpose is to assess whether or not ventilation systems can really be assessed based on assumptions of well-mixed behaviour within indoor spaces. There is a section on the quality assurance of the diffusion tubes and the chemiluminescence analyser including operating procedure and data post-processing.

Chapter 4 outlines the levels of exhaust emissions measured within the Neville Hill railway depot under static train testing conditions with no applied load, to address research question 1. Experimental data obtained from 3 different trains using a PEMS (portable emission measuring system) kit is compared for different pollutant concentrations, and mass flow rates are estimated for each of the 3 trains for each of the notch power settings. Additional emissions data obtained externally from the RSSB, from a load bank test of a 170 train is also compared against the PEMS (Portable Emissions Measuring System) data from the 3 trains surveyed in terms of pollutant concentrations and mass flow rates. It also discusses a WTW analysis

within the rail sector to address research question 2. The potential for the use of alternative fuels within UK is rail discussed, along with current UK policy, through research question 3.

Chapter 5 outlines the data analysis of the air quality measurements at the Neville Hill railway depot using static air quality measurements to address research question 4. The changes in monthly NO_2 concentration are assessed in the Neville Hill railway depot using diffusion tubes at different heights. Additionally, diffusion tubes are used to determine the indoor concentrations of NO_2 at different positions at Neville Hill and 3 additional railway depots, namely Allerton, Heaton and Newton Heath. This chapter also evaluates a box model to predict indoor NO_2 concentrations in the Neville Hill repair shed using point source emission data and indoor NO_2 concentration data as part of research question 4. A time invariant steady state box model is used to evaluate the indoor air quality within the one of the depot's shed (repair shed). It also outlines the data analysis of the air quality measurements at the Manchester Victoria station to address research question 4. Diffusion tubes are used to determine the concentrations of NO_2 at different positions within the train station.

Chapter 6 outlines the data analysis of the short time-scale air quality measurements at the Neville Hill railway depot using transient air quality measurements to address research question 4. This involves combining train logging information with air quality measurements to estimate the most polluting train type in the Neville Hill railway depot.

Chapter 7 addresses the conclusions of the thesis, in particular relating to the 4 research questions and the 3 objectives of the project thesis. It also outlines future work.

Chapter 2 Literature Review

2.1 Introduction

The majority of trains throughout the world are fuelled by one of two fuel sources, diesel and electricity. Diesel trains, however, emit significant amounts of particulate matter and nitrogen oxides, which have had an adverse effect on air quality as reflected by poor air quality incidents seen at Birmingham New Street station and the Neville Hill railway depot (BBC, 2020; Jackson, 2018).

Diesel trains were first introduced in 1904, using the diesel fuel developed by its' namesake Rudolf Diesel. The pollutants emitted from these diesel fuelled trains can have a number of negative environmental and personal health effects when released in excessive quantities. Pollutants can be categorised into two fields, primary and secondary pollutants. Primary pollutants include nitrogen oxides, carbon dioxide, sulphur dioxide (SO_2), carbon monoxide (CO), volatile organic compounds (VOC) and particulate matter. Primary pollutants contribute directly to the global warming effect with carbon dioxide the most significant pollutant in this field. Secondary pollutants such as NO_2 (nitrogen dioxide) and O_3 (ozone) lead to the formation of photochemical smog. The relevance of both primary and secondary pollutants to this project is that many of the diesel multiple unit (DMU) trains operated by the train operator, Northern Rail have no aftertreatment system fitted, and as a consequence release a large amount of pollutants from the exhaust pipe of each of the DMUs into the ambient air. This can be problematic in a confined indoor, setting such as a railway depot, in which the significant volume of exhaust pollutants in the indoor atmosphere, can expose workers to elevated levels of pollutants such as NO_2 and PM. NO_2 and PM are notable pollutants which cause negative, health effects. Specific details regarding the negative health effects of a selection of exhaust pollutants will be discussed in the next section.

2.2 Diesel engine fundamentals

Internal Combustion Engines (reciprocating) are devices used to convert chemical energy, in the form of fuel into kinetic and thermal energy using combustion as the driving force and can be divided into two categories, based on the number of strokes it takes to complete one thermodynamic cycle. The four stroke engines are used in road and rail transportation vehicles while the two stroke cycle is being used in smaller engines, such as lawnmowers and large marine engines.

Diesel engines trace their origin back to the French-born inventor Rudolf Diesel, whose name is lent to the engine's name. He developed an engine to combust fuel via compressed air which auto-ignites diesel fuel. Rudolf Diesel's engine operated at a greater efficiency than was currently operational at the time, steam engines and gasoline (Otto cycle) engines, which had a very, poor efficiency. In addition, his diesel engine aimed to address two concerns:

1. "Lack of control of the compressed air temperature
2. High heat losses" (Diesel, 1892)

His development of first a procedure, for diesel combustion and later an engine led to the foundations for modern diesel engines of today. (Diesel, 1900; Diesel, 1892; Mollenhauer and Tschöke, 2010a).

2.2.1 Key terms

The following terms are important to understanding engines and these terms will be referenced throughout this thesis.

Torque (TQ): this is the rotational force around a fixed point and within engines refers to amount of driving force required to turn the crankshaft. It is measured in units of Nm or lb-ft (Inc., 2011). It can be measured using a dynamometer at an engine testbed.

Engine Load: this is defined as the "indicated percentage of peak available torque" (Alessandrini et al., 2012)

Power (PW): this refers to the amount of mechanical power required to move a vehicle at a given velocity. It can be calculated by multiplying the product of the torque (T) and rpm and divided by a conversion factor of 9549.3, as seen in equation 2.1. Power is measured in units of kW.

$$PW = \frac{TQ\ rpm}{\frac{1}{2\pi} \times 60 \times 1000} \tag{2.1}$$

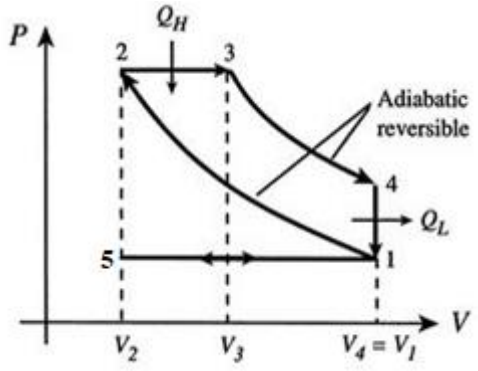
where *PW* is Power in kW, **TQ** is Torque in N m^{-1} and **rpm** is revolutions per minute

Crank Angle (CA): this refers to the angle at which the crankshaft is positioned during the clockwise rotation of the crankshaft. It is measured in units of °.

Ignition delay: this refers to the time delay between the start of the engine's fuel injection (SOI) and the start of engine combustion (SOC). It is measured in units of crank angles and/or milliseconds

2.2.2 Four stoke engine cycle

Spark Ignition (SI) petrol and Compression Ignition (CI) diesel vehicles, both operate on four strokes to complete a thermodynamic cycle. Each of these strokes have an associated phase, which comprise intake, compression, combustion and exhaust. Where the petrol (port fuel injection) and diesel engine differ, is in the fuel entry point. In diesel engines, fuel enters fuel enters at the compression stage, with air entering solely at the intake stage. Under ideal conditions, diesel can be represented by the diesel cycle. As this thesis, only considers diesel engines with reference to the rail sector, detailed specifics for the four stroke cycle will only be provided the diesel cycle. The diesel cycle describes the four strokes of the diesel engine with stages of intake, compression, expansion and exhaust. Figure 2.1 shows a P-V diagram of the ideal diesel cycle.



5-1 Intake Stroke

1-2 Isentropic Compression, 2-3 Constant Pressure Expansion (Fuel injection & combustion)

3-4 Isentropic Expansion, 4-1 Constant Volume Cooling

1-5 Exhaust Stroke

Figure 2.1: Diesel Cycle (Quattrochi, 2006)

In the intake stage, air enters the combustion chamber. The air is then compressed during the second stroke as the piston moves from BDC (Bottom Dead Centre) to TDC (Top Dead Centre). The compression ratio is much higher than that of the Otto Cycle with a ratio of greater than 12:1 (Heywood, 1988b). Fuel is introduced to the cycle during the latter part of the second stroke during which mixing with air commences. Fuel injection ceases just after the second stroke's completion. The energy from the combustion, pushes the piston downwards and results in an expansion of the mixture. The combustion products exit the combustion chamber via the exhaust valve opening and the piston moving upwards, with heat rejection occurring. The piston reaches TDC with the exhaust valve closing. This completes the final stroke of the Diesel cycle. Within the entire four stroke cycle, the crankshaft completes two revolutions equating to a 720° crank angle rotation.

Diesel's majority straight-chain structure and lower ignition temperature allow it to autoignite with compressed air. Petrol, however, requires a heating element in order to combust. A comparison of the diesel and petrol cycles are given in Table 2.1.

Table 2.1 Comparison of the Otto and Diesel cycle (Manning, 2012)

	Otto Cycle	**Diesel Cycle**
Fluid	Petrol	Diesel
Ignition	Requires spark plug	Auto-ignition
Compression ratio	9:1 to 14:1	>17:1
Fuel entry point	Intake Stage	Combustion Stage
Autoignition T (°C)	>350	240

2.2.3 Combustion principles

There are two types of injection system for the diesel engine: direct injection (DI) and indirect injection (IDI). In direct injection, the fuel enters the combustion chamber directly via a nozzle spray. In indirect injection, the fuel enters in an area before the combustion chamber known as the pre-chamber or auxiliary chamber. The combustion process can be split into three stages, pre-mixed combustion followed by rate-controlled combustion and finishing with late combustion. Typically, these three stages of combustion can be characterised graphically as a function of the crank angle, as seen in Figure 2.2.

2.2.3.1 **Direct Injection**

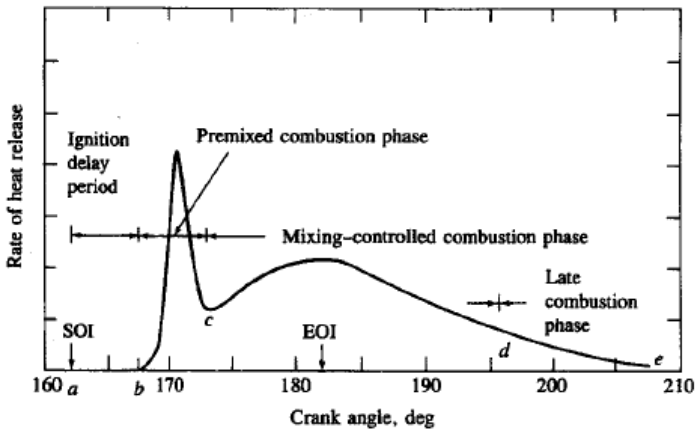


Figure 2.2: Combustion Cycle graph for Direct Injection Diesel engine (Heywood, 1988a)

The first stage, points a to b in Figure 2.2, accounts for the ignition delay. This delay acts to maintain the maximum cylinder pressure below the tolerance of the maximum engine pressure. In direct injection systems, fuel enters the combustion chamber via a nozzle from which fuel is sprayed into the combustion chamber. In the pre-mixed combustion stage (b to c), fuel injected during ignition delay period autoignites and combustion begins. During this period, the highest rate of heat release is observed, with a minor change in the crank angle. This high rate of heat release also gives rise to a high cylinder pressure. Following premixed combustion, the combustion continues at a slower rate (c to d). During this period, the majority of heat release occurs. The final stage (d to e), is the final stage combustion, in which the remaining unreacted fuel is combusted with air. The rate of heat release gradually descends to minimal levels (Heywood, 1988c). To ensure good mixing, air must enter in a swirling motion, to improve mass transfer. This can be achieved in one of two ways, either by pre-swirling the air within the inlet port or by inducing swirl inside the combustion chamber by aiming the inlet air at a tangent to the cylinder wall. To improve combustion, a small droplet size of fuel within the nozzle aids atomisation as well as using a higher pressure to inject the fuel (Heywood, 1988c). A glow plug is present in the combustion chamber and is utilised if the temperature of the fluid is too low, for auto-ignition; typically in cold weather conditions [17].

Due to the spray mechanism, there are regions within the combustion chamber, shown in Figure 2.3, which lead to air pollution, with NO_x and soot forming. In the areas outside of the fuel spray, these are high temperature regions with excess air and under these conditions NO_x forms. Outside of the flame zone, the temperature is low, so the hydrocarbons do not form, resulting in unburnt hydrocarbons, which are another

impurity in the exhaust stream. In air-deficient zones, CO forms which leads to soot formation; a form of particulate matter.

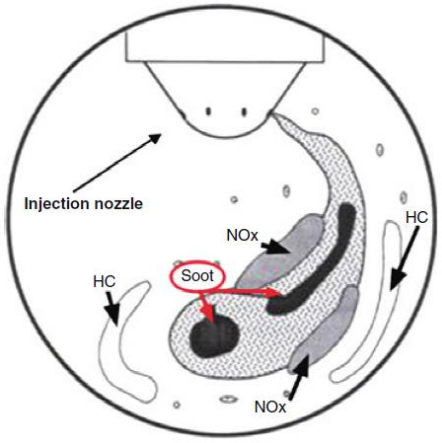


Figure 2.3: Pollutants formation in the combustion chamber (Mollenhauer and Tschöke, 2010b)

2.3 Primary Pollutants

2.3.1 Nitrogen Oxides (NO_x)

Nitrogen oxides are predominately two gases: nitric oxide (NO) and nitrogen dioxide (NO_2). They are formed naturally and through anthropogenic sources. Anthropogenic sources include vehicle emissions and industrial plants. Within vehicles, nitrogen oxides are formed from the combustion of fuel and air, in which the nitrogen in the air reacts with oxygen to form NO_x at high engine temperatures. Other nitrogen oxides such as nitrous oxide (N_2O) form a very small composition of the nitrogen oxides mixture, and are often neglected in discussions of tailpipe emissions.

2.3.1.1 **Nitric Oxide (NO)**

2.3.1.1.1 Nitric oxide formation

Nitric oxide is formed via the Zeldovich mechanism illustrated in equations 2.2 – 2.5, in which oxygen reacts with nitrogen. The overall mechanism is summarised in equation 2.2 (Flagan and Seinfeld, 1988).

$$N_2 + O_2 \rightarrow 2NO \quad (2.2)$$

Analysing the mechanism in stages, within the first stage, shown in equation 2.3, nitrogen reacts with the oxygen radical in a highly endothermic reaction to produce nitric oxide and atomic nitrogen.

$$O + N_2 \leftrightarrow NO + N \quad (2.3)$$

The nitrogen atom can then further react with oxygen to produce further NO, as seen in equation 2.4.

$$N + O_2 \leftrightarrow NO + O \quad (2.4)$$

A third reaction, shown in equation 2.5 at near-stoichiometric conditions reacts nitrogen with a hydroxyl (OH) to form NO (Sher, 1998c).

$$N + OH \leftrightarrow NO + H \quad (2.5)$$

NO has less serious health impacts and is only of concern when it is converted into NO_2 via interactions with ozone.

2.3.1.2 **Nitrogen Dioxide (NO_2)**

Nitrogen dioxide can form from many different sources, including engine combustion. Within the engine combustion process, primary NO_2 is formed at the flame front, as illustrated in equations 2.6 and 2.7, with M denoting a third body species.

$$NO + HO_2 \leftrightarrow NO_2 + OH \quad (2.6)$$

$$NO + O\ (+M) \rightarrow NO_2\ (+M) \quad (2.7)$$

2.3.2 Particulate Matter (PM)

Particulate matter forms from the incomplete combustion of hydrocarbons, and can take the form of soot or a liquid form. During the combustion process in an engine, some of the hydrocarbons do not combust to gaseous products such as CO_2 and instead form solid particles. The two main regulated particle size fractions in the UK are PM_{10} and $PM_{2.5}$. PM_{10} is defined by AQEG as “airborne particulate matter passing a sampling inlet with a 50% efficiency cut-off at 10 µm aerodynamic diameter and which transmits particles of below this size” (DEFRA). $PM_{2.5}$ is defined as “passing a sampling inlet with a 50% efficiency cut-off at 2.5 µm aerodynamic diameter and which transmits particles of below this size” (DEFRA). A graph of the different particle size ranges including $PM_{2.5}$ and PM_{10} are shown in Figure 2.4 by Kittelson (Kittelson, 1998). As Figure 2.4 shows, particles are divided into three subgroups, the nuclei group, the accumulation group and the coarse mode.

The nuclei mode is the smallest size range of particles and covers nanoparticles with a diameter (Dp) < 50 nm. They arise due to homogenous nucleation in the atmosphere and via high temperature emission sources [29]. The nuclei particles have a low mass per particle and have a high tendency to Brownian motion resulting in an efficient deposit of the nuclei particles to a surface. The second subgroup is the accumulation mode which covers particles between 50 nm and 1 µm. Due to their larger size, they are weakly affected by Brownian motion. Particles form in the accumulation mode due to the growth of nuclei mode particles and coagulation of nuclei mode particles. The third subgroup is the coarse particle mode which includes particles > 1 µm. Particulate matter in the $PM_{2.5}$ and PM_{10} size ranges have a number of negative health effects including respiratory illness and cardiovascular illness. According to the COMEAP, “for every decrease of 1 µg m^{-3} of $PM_{2.5}$, there will be an increase in life expectancy of 1.5-3.5 days per individual across England & Wales” (AQEG, 2005).

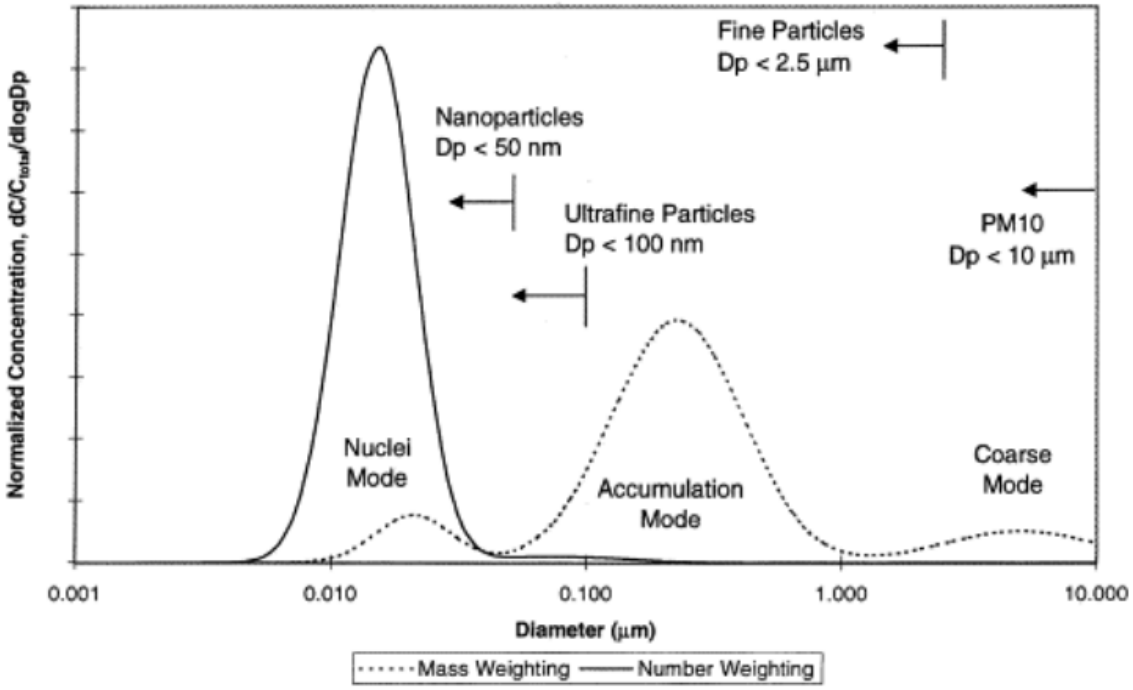


Figure 2.4 Particulate matter formation, reproduced from Kittelson (Kittelson, 1998)

Kittelson has conducted extensive work in the area of particulate matter measurements and his graphic for particle size distributed, shown in Figure 2.4, is widely reproduced as a reference for the size distribution for normalised concentrations of particulate matter with increasing diameter (Kittelson, 1998).

2.3.3 Elemental carbon (EC)

Particulate matter, can be also be sub-divided into categories based on composition. One of this components is elemental carbon (EC). EC is defined by AQEG as "black carbon (soot) formed from unburnt formed during high temperature combustion of fossil fuels such as coal, natural gas and oil (diesel and petrol) and biomass fuels such as wood chips" (AQEG, 2005).

2.3.4 Organic carbon (OC)

Organic carbon (OC) is another constituent of particulate matter and "forms from unburnt hydrocarbons and partially burnt hydrocarbons arising from lubricant oil and engine fuel" (Grennan-Heaven and Gibbs, 2020b).

2.3.5 Respirable dust (RD)

Respirable dust is defined the HSE (Health & Safety Executive) as the “the fraction that penetrates to the gas exchange region of the lung” (HSE, 2005d). It is measured by using a “sampling a distribution of particles (~ <10 µm) with a median diameter of 4.3 µm” (HSE, 2011).

2.3.6 Volatile Organic Compounds (VOC)

Volatile organic compounds are defined by the UK government (2012 No. 1715) as “any organic compound having an initial boiling point less than or equal to 250°C measured at a standard pressure of 101.3 kPa” (UKGov, 2012). Aromatics such as benzene, toluene, ethylbenzene and xylene, referred to collectively as BTEX, are examples of VOC’s and have a number of negative health effects.

Benzene under a short term exposure “can cause irritation to the eye, nose and throat” in addition to coughing (EPA, 2016). In large exposure doses, it can lead to “swelling of the airways and a build-up of fluid in the lungs” (EPA, 2016). Toluene in the vapour form under short term exposure “can cause drowsiness, dizziness and headaches” (EPA, 2016). Exposure to large quantities of toluene can result in the “permanent damage of the nervous system, heart problems and in extreme cases, death” (EPA, 2016). Ethylbenzene has similar health effects to benzene exposure. Under a small exposure to ethylbenzene, this can result in “throat irritation and chest constriction, irritation of the eyes, and neurological effects such as dizziness” (EPA, 2016). In the case of chronic exposure to ethylbenzene, the effect on humans is not clearly defined with “conflicting results regarding its effects on the blood” (EPA, 2016). Xylene inhalation in small quantities “can cause irritation to the nose, throat and lungs” (Agency, 2010). Xylene exposure in large amounts either through inhalation or ingestion “can cause dizziness, headaches, confusion, heart problems, liver and kidney damage and coma” (Agency, 2010). VOC’s can react with NO in the atmosphere to produce ozone in the global reaction, shown in equation 2.8, with the term hv indicating a wavelength of sunlight (Sher, 1998a).

$$VOC + NO_x + hv \rightarrow O_3 + HNO_3 + Organics \qquad (2.8)$$

2.3.7 Total Hydrocarbons (THC)

Total hydrocarbons (THC) refers to the hydrocarbon emissions which result from incomplete combustion from compounds of hydrogen and carbon only. They

include some VOC's however VOC's may contain other elements such as oxygen (CITEAIR, 2007; JM, 2017). The term HC (Hydrocarbons) is often used in many studies in the US and Germany and is this study will be assumed to be equivalent to THC.

2.3.8 Carbon Monoxide (CO)

Carbon monoxide is produced from the incomplete combustion of fuel within an engine, due to insufficient air as seen in equation 2.9, for the general reaction of the incomplete combustion of an alkane with the formula C_xH_y (GUPTA, 2012).

$$C_xH_y + (x-0.5a+0.25)\ O_2 \rightarrow a\ CO + (x-a)\ CO_2 + 0.5y\ H_2O \quad (2.9)$$

where a is the stoichiometric coefficient of CO, x-a is the stoichiometric coefficient of CO_2, x is the number of moles of carbon from reaction balance, 0.5y is the stoichiometric coefficient of hydrogen from reaction balance.

One of the effects of carbon monoxide is that it reduces the ability of oxygen to combine with the haemoglobin in the bloodstream, and thereby reducing the ability to transport oxygen from the lungs to the other parts of the body (Dash and Dash, 2009; Springer, 2012). In the atmosphere, CO can react with an OH radical to form CO_2 as seen in equation 2.10 (Clarke and Tomlin, 2007).

$$CO + OH \rightarrow CO_2 + H \quad (2.10)$$

2.4 Secondary Pollutants

Secondary pollutants include ozone, nitrogen dioxide, hydrogen peroxide, peroxyacetyl nitrate (PAN) and particulates (Colls, 2002a). Secondary pollutants lead to the formation of photochemical smog which deteriorates air quality and impacts plant and animal ecosystems. Regions affected by photochemical smog, result in a grey-cloud landscape. In addition, the photochemical smog has a negative effect on crop yields and tree morphology (Dupont and Tomlin, 2017). Secondary pollutants have a set of associated negative health effects which will be discussed in the next sub-section (State).

2.4.1 Ozone (O_3)

Ground level ozone is formed from the reaction of NO_x with VOCs from engine emissions in the presence of sunlight as seen earlier in the simplified overall equation in equation 2.8 (vanLoon et al., 2011). The expanded form of the general

reaction where VOCs assist with the conversion of NO to NO_2 is shown in equations 2.11-2.13.

$$RH + OH \rightarrow R \quad (2.11)$$

$$R + O_2 \rightarrow RO_2 \quad (2.12)$$

$$RO_2 + NO \rightarrow NO_2 \quad (2.13)$$

Firstly, this begins with the photolysis of NO_2 in the atmosphere producing NO and ground state oxygen as seen in equation 2.14 (Colls, 2002a).

$$NO_2 + hv \rightarrow NO + O \quad (2.14)$$

This ground state oxygen reacts with dioxygen and a third body, M which does not take place in the reaction but is required for energy absorption, to produce ozone, as seen in equation 2.15. The third body (M) is typically dinitrogen or dioxygen (vanLoon et al., 2011).

$$O + O_2 + M \rightarrow O_3 + M \quad (2.15)$$

Ozone (O_3) itself is a “highly reactive substance” and has a number of negative health effects including “irritation of and damage to the small airways of the lungs” (HSE, 2014). A large exposure to ozone can “result in lung damage” (HSE, 2014).

2.4.2 Nitrogen Dioxide (NO_2)

Nitrogen dioxide can form from many different sources, including engine combustion and via the reaction of NO in ambient air. Nitrogen dioxide health effects include “inflaming the lining of the lungs” and a reduced immune system response to lung infections, leading to “wheezing, coughing and colds” (AusGOV, 2005). Exposure to nitrogen dioxide can affect people suffering with asthma, with a consequence of “more frequent and more intense asthma attacks” (AusGOV, 2005). Nitrogen dioxide can also form in a secondary reaction from reacting ozone with nitric oxide, as seen in equation 2.16. The nitric oxide arises from fossil fuel combustion and when exposed to ozone, additional quantities of NO_2 can be generated (Sher, 1998b).

$$NO + O_3 \rightarrow NO_2 + O_2 \quad (2.16)$$

2.4.3 Particulate Matter (PM)

Secondary particulate matter as per the EEA definition are “pollutants that are partly transformed into particles by photo-chemical reactions in the atmosphere (EEA, 2018)”. Sources of secondary particulate matter include: “power plants and industrial processes such as the oil refining”(EPA, 2020).

2.5 Alternative fuels

The NO_2 and PM described previously, have contributed to the poor levels of air quality in some of the major cities in the world (WHO, 2018). One of the reasons for this decline in air quality is due to the utilisation of fossil fuels in large quantities of vehicles, with diesel in particular, emitting large amounts of particulate matter and NO_x. One way in which this could be mitigated is through the use of clean, alternative fuels, within diesel engines. Alternative fuels can include renewable and non-renewable fuels. Hydrogenated Vegetable Oil (HVO) is an example of a renewable fuel and Gas to Liquids (GTL) is an example of a non-renewable fuel. The advantages of alternative fuels in comparison to diesel are:

1. Reducing CO_2 emissions
2. Reducing pollutant emissions
3. Energy supply security

2.5.1 Gas to Liquids (GTL)

GTL is a fuel derived from natural gas which are processed into a near similar diesel-like fuel using the Fischer-Tropsch Synthesis process, as shown in Figure 2.5. The fuel specification for a typical GTL fuel is shown in Table 2.2.

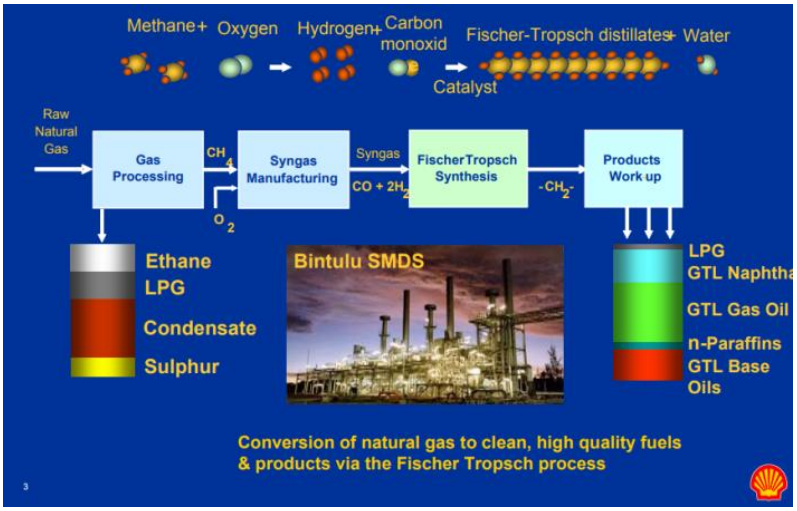


Figure 2.5 GTL production process (Hoek, 2006)

Table 2.2 GTL Fuel, Shell internal specification 400008850 – Nov 2016, compared against the diesel specification of EN 590 (Shell, 2016; BS, 2013)

Property	**Unit**	**Min**	**Max**	**EN 590:2013**
Cetane No.		70		≥ 51
Density at 15°C	kg/m^3	765	800	820-845
Total aromatic content	%m/m		1	-
Flash point	°C	> 60		> 55
Ash content	%m/m		0.01	≤ 0.01
Water content	mg/kg		150	≤ 200
Total contamination	mg/kg		24	≤ 24
Copper strip corrosion (3 hr at 50°C)	-	Class 1	Class 1	Class 1
Oxidation stability	g/m^3		25	≤ 25
Oxidation stability	hr	20		≥ 20
Lubricity at 60°C	µm		460	≤ 460
Kinematic viscosity at 40°C	mm^2/s	2	4.5	2-4.5
Distillation 95% recovered	%v/v		360	≤ 360

There are a number of reasons for lower emissions from GTL than diesel. Firstly GTL has a lower aromatic content ranging between 0.2 and 1.0 vol% as compared to diesel which has a much larger aromatic content of typically >15 vol% (Sajjad et al., 2014; Concawe, 1992). The lower aromatic content of GTL leads to a reduced adiabatic flame temperature which can lower the quantity of NO_x produced. In addition, the lower aromatic content of GTL, results in a reduced soot formation.

GTL has a higher cetane number than diesel with a cetane number of 70 or greater in comparison with diesel which has much lower cetane number of about 55 (Bassiony et al., 2016). A higher cetane number for GTL indicates improved combustion characteristics due to a shorter ignition delay time and hence lower quantities of carbon monoxide and unburnt hydrocarbon produced from the emissions of GTL. The absence of PAH's (Polycyclic Aromatic Hydrocarbon) in GTL, results in a reduction of NO_x when using higher exhaust gas recirculation ratios without a smoke penalty (Sajjad et al., 2014; Bassiony et al., 2016; Wu et al., 2020).

2.5.2 Hydrogenated Vegetable Oil (HVO)

HVO or renewable diesel contains simple straight chain hydrocarbon and is produced by removing oxygen from the triglycerides of the vegetable oil/animal fat feedstock through hydrotreating and isomerisation, as shown in equation 2.17 using a hydrogenation catalyst. In this reaction three alkanes are produced, two of which have an alkane radical to the formula of C_nH_{2n+2} in addition to carbon dioxide and water. The process flow diagram is shown in Figure 2.6. The typical fuel specifications for HVO are shown in Table 2.3 and are compared with standard diesel (Neste, 2016; BS, 2013; BS, 2016).

$$(R\text{-}CH_2OCO\text{-})_2\text{-}CH_2CHCH_2OCO\text{-}R' \rightarrow 2\ CH_3CH_2\text{-}R + CH_3\text{-}R' + 4H_2O + CO_2 + C_3H_8 \quad (2.17)$$

where R: Alkane Radical with formula C_nH_{2n+2} where n is a number greater than or equal to 1.

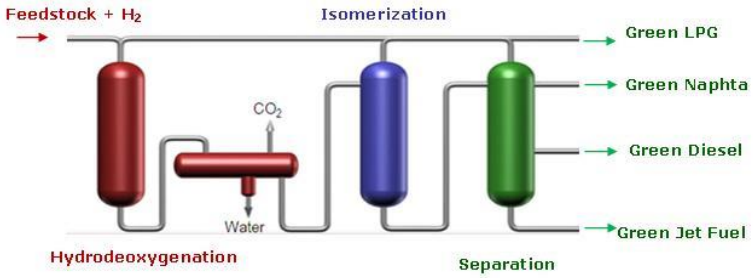


Figure 2.6 HVO production process flow diagram (Eni, 2014)

HVO offers a number of advantages, as well being an alternative, renewable fuel, it offers a high cetane number, a high stability and reductions in PM in comparison to standard diesel. A higher cetane number results in a greater fuel performance, in terms of a shorter ignition delay time (Wu et al., 2017). A high stability indicates that the fuel will not degrade in storage. HVO's disadvantages are that it is has much higher cost than either diesel and if produced from certain

vegetable oil feedstocks, creates an issue with diverting food crops for fuel production (Vojtisek-Lom et al., 2017; Wu et al., 2017).

Table 2.3 HVO fuel specification from Neste Oil, compliant to EN15940:2016 and EN 590 standards (Neste, 2016; BS, 2013; BS, 2016)

Property		**Neste Oil**	**EN 15940:2016 Class A**	**EN 590:2013**
Appearance at 25°C		Clear & Bright		
Cetane Number		> 70	>70	≥ 51
Density at 15°C	kg/m^3	770-790	765-800	820-845
Total aromatics	%m/m	< 1	≤ 1.1	-
Sulphur content	mg/kg	< 5	≤ 5	≤ 10
Flash point	°C	> 61	> 55	> 55
Carbon residue on 10% distillation residue	%m/m	≤ 0.1	≤ 0.3	≤ 0.3
Ash content	%m/m	< 0.001	≤ 0.01	≤ 0.01
Water content	mg/kg	≤ 200	≤ 200	≤ 200
Total contamination	mg/kg	≤ 10	≤ 24	≤ 24
Copper strip corrosion (3h at 50°C)		Class 1	Class 1	Class 1
Oxidation stability	g/m^3	≤ 25	≤ 25	≤ 25
Oxidation stability	hr		≥ 20	≥ 20
Lubricity at 60°C	µm		≤ 460	≤ 460
Kinematic viscosity at 40°C	mm^2/s		2-4.5	2-4.5
Distillation 95% recovered	%v/v		≤ 360	≤ 360

2.5.3 Life cycle analysis

Life cycle analysis (LCA) is a method used to evaluate the environmental impact of a product through its' life cycle encompassing extraction and processing of

the raw materials, manufacturing, distribution, use, recycling, and final disposal (Ramachandra Rao, 2006). It can be used to assess the carbon footprint of transportation fuels. This is done by calculating the mass of carbon dioxide equivalent which is commonly expressed as kg CO_2-e and corresponds to the mass in kg of carbon dioxide released into the atmosphere based on a chosen functional unit. Functional unit examples include litres of fuel, or energy content of the fuel in GJ or MJ or the mass of the fuel in kg. LCA includes WTT and TTW. The system boundaries for the calculation can determine whether to include only at the point of source of combustion, known as Tank to Wheel (TTW) or to include emissions associated with the upstream process such as extraction and refining required to produce the fuel, termed well to tank (WTT). For diesel, the WTT boundary is set from when crude oil is first extracted from an oil well to diesel being filled into a vehicle fuel's tank.

2.5.3.1 LCA Software evaluation

There are a number of LCA software packages for conducting WTT and WTW studies. These include GREET, Biograce, Bio-D, GHGenius Canada. The key features of these packages are given in Table 2.4. GREET is a US software and is more catered for the North America market. Similarly, GH-Genius Canada is a Canadian software also catered for the North American market with detailed data for North American feedstocks. Biograce and Bio-D are European software packages utilised by the EU with electricity data for individual EU countries including the UK.

Table 2.4 Key comparison of different LCA packages

	GREET	**Biograce**	**Bio-D**	**GH-Genius**
Software style	Standalone program	Excel	Excel	Excel
Version	2029	V4d	2017	V5.0f
Database	US + generic non-US	EU + generic non-EU	EU + generic non-US	US, Canada, generic non-North America
HVO in software	As Jet fuel cut	Yes	Yes	Yes
GTL in software	Yes	Yes	Yes	Yes

UCO in software	Yes as yellow grease HVO	Yes for Biodiesel UCO	Yes for WCO Biodiesel and WCO HVO	Yes for Yellow grease Biodiesel
CO_2 eq. (g kWh^{-1})	Yes	Yes	Yes	Yes
Total CO_2 (g kWh^{-1})	Yes	Yes	Yes	Yes
NOx (g kWh^{-1})	Yes	No	No	No
NO_2 (g kWh^{-1})	Yes	No	No	Yes
PM_{10} (g kWh^{-1})	Yes	No	No	Yes

UCO Used cooking oil, WCO Waste cooking oil

2.5.4 Summary of alternative fuels

The significance of this initial assessment of alternative fuels is in providing an option for Northern Rail to potentially trial within their DMUs, in order to minimise the emissions associated with diesel fuel as well as maintaining an optimum performance in terms of fuel consumption. It appears as though GTL and HVO are viable options for Northern Rail, in terms of emission reduction and their 'drop-in' nature in which no engine modification is required for usage are advantageous qualities for these two fuels. This in turn could improve the levels of air quality, as a lower quantity of harmful pollutants would be released into the atmosphere. These fuels, were chosen in particular because of their availability and exhaust emission reduction potential. Biodiesel was not chosen for consideration, since in most cases it has a negative effect on NO_x emissions, with in an increase in NO_x, with the most probable cause, theorised by Lapuerta et al. to be due to 'the advance of injection start when compared to diesel fuel' (Sharp et al., 2005; Lapuerta et al., 2008).

2.6 Rail Emission legislation

With regards to trains themselves, there are a series of exhaust emissions standards in place since 2002. The earliest UK standard applicable to trains was developed by the UIC (Union Internationale des Chemins de fer) in 2002, as UIC I. This UIC I standard was only advisory within the UK and there was no strict enforcement of this standard. The UIC I, of 2002 governs non-road vehicles and has an emission criteria for CO, HC and NO_x as seen in Table 2.5 (DieselNet, 2007). In 2003, an updated version of the UIC, known as UIC II was introduced with lower emission limits for non-road vehicles as shown in Table 2.5. In 2006, the EU

introduced new limits, known as Stage III limits applicable for trains in the non-road sector, with the Stage IIIB variant introduced in 2012, as seen in Table 2.6. Stage IV limits of 2014 introduced lower HC, PM and NO_x limits for non-road diesel engines as seen in Table 2.7 however these do not apply to rail traction engines. There is a plan for a tighter non-road emission standard for trains, under the title, Stage V outlined in Table 2.8 (DieselNet, 2016). Trains in the UIC I era of 2002 were tested using ISO 8178 Part 4, Test Duty Cycle F, Stage IIIB rated trains of 2012 onwards are tested via ISO 8178:C1, detailed in Table 2.9 for the former and Table 2.10 for the latter. Many of Northern Rail's leased DMU fleet however, pre-date all of these standards, with many DMUs dating back to the 1980's and so are operating under the premise that there are no emission limits for their trains, colloquially referred to as the 'grandfather rights' within the train industry. A lack of aftertreatment exhaust systems in Northern Rail's older DMUs (15X and 170) creates the conditions for elevated levels of pollutants such as PM, NO_x, THC and CO to be released within a confined railway depot.

Table 2.5. UIC locomotive emission standards (DieselNet, 2007)

Stage	Date	Power (P)	Speed (v)	CO	HC	NOx	PM
		kW	rpm	g kWh^{-1}			
UIC I	up to 31/12/02			3	0.8	12	-
UIC II	01/01/03	P ≤ 560		2.5	0.6	6.0	0.25
		P > 560	v > 1000	3	0.8	9.5	0.25[a]
			v ≤ 1000	3	0.8	9.9	0.25[a]

Table 2.6. Stage III A/B emission standards for rail traction engines (DieselNet, 2016)

Category	Net Power	Date	CO	HC	HC+NOx	NOx	PM
	kW		g kWh^{-1}				
Stage III A							
Railcar							
RC A	P > 130	2006	3.5	-	4.0	-	0.2
Locomotive							
RL A	130 ≤ P ≤ 560	2007	3.5	-	4.0	-	0.2
RH A	P > 560	2009	3.5	0.5	-	6.0*	0.2

Stage III B							
Railcar							
RC B	P > 130	2012	3.5	0.19	-	2.0	0.025
Locomotive							
R B	P > 130	2012	3.5	-	4.0	-	0.025

where RC is railcar, RC A is railcar for Stage IIIA, RL is rail locomotive, RL A is rail locomotive for Stage IIIA between 130-560 kW, RH A is rail locomotive for Stage IIIA above 560 kW, RC B is railcar for Stage IIIB, R B is rail locomotive for Stage IIIIB

Table 2.7 Stage IV emission standards for non-road diesel engines (DieselNet, 2016)

Category	**Net Power**	**Date**	**CO**	**HC**	**NOx**	**PM**
	kW		g kWh^{-1}			
Q	130 ≤ P ≤ 560	01/2014	3.50	0.19	0.4	0.025
R	56 ≤ P < 130	10/2014	3.50	0.19	0.4	0.015

Table 2.8. Stage V emission standards for rail traction engines (DieselNet, 2016)

Category	**Net Power**	**Date**	**CO**	**HC**	**NOx**	**PM**	**PN**
	kW		g kWh^{-1}				kWh^{-1}
RLR-v/c-1 (Railcars)	P > 0	2021	3.50	0.19	2.00	0.015	$1×10^{12}$
RLL-v/c-1 (Locomotives)	P > 0	2021	3.50	4.00		0.025	-

where RLR is railcar for Stage V, RLL is rail locomotive for Stage V

Table 2.9 ISO 8178-4 test cycle F for rail traction

Mode number	**1**	**2**	**3**
Speed	Rated speed	Intermediate speed	Low-idle speed
Torque	100	50	0
Weighting factor	0.25	0.15	0.6

Table 2.10 ISO 8178-4 test cycle C1 for rail traction

Mode number	**1**				**2**			**3**
Speed	Rated speed				Intermediate speed			Low-idle speed
Torque	100	75	50	10	100	75	50	0
Weighting factor	0.15	0.15	0.15	0.1	0.1	0.1	0.1	0.15

2.6.1 Previous emission testing in the rail sector

2.6.1.1 **Testing in Europe**

The RSSB (Rail Safety and Standards Board) have conducted test-bed trials for many of the engines utilised in Northern Rail's DMU fleet. Notably, this includes the Cummins LTA-10R, the Cummins NTA855R1, the Cummins NTA855R3, the Cummins NTA855R5 and the Perkins 2006-TWH engines. The trials were conducted in 2006 using an engine dynamometer by the company, mi Technology in Preston (Ian, 2006b; UIC, 2007) with the engines tested, as per the ISO 8178 Part 4, Test Duty Cycle F, which is written in a simplified notation as ISO 8178:F. The ISO 8178:F involves testing the engine under 3 conditions, low-idle conditions at 0% torque, 50% torque at intermediate speed and 100% torque at the rated speed. The engines used for testing were due for overhaul and were removed from the vehicles of 3 participating TOC's (train operating companies), First Great Western (FGW), Arriva Trains Wales (ATW) and South West Trains (SWT). N.B. The South West Trains (SWT) franchise operated by Stagecoach ceased in 2017 and this has been transferred to a new franchise, South Western Railway (SWR) in 2017.

Tests were conducted for approximately 15 minutes on each condition under the three conditions as per the testing regime of the ISO 8178:F standard. For each engine, two different fuels were tested, gas oil, and sulphur free diesel (SFD) with the emission results in Table 2.11 for the pollutants of NO_x, PM, CO, HC and CO_2. The emissions were determined in units of g kWh^{-1} representing a weighted value at 0% torque, 50% torque and 100% torque. (Ian, 2006b). Lower emissions for all pollutants were observed using SFD in comparison to gas oil.

Table 2.11 Exhaust Emissions engines from TOC's using either gas oil or SFD fuel (Ian, 2006b)

Train Model	Fuel	Engine	NO_x g kWh^{-1}	PM g kWh^{-1}	CO g kWh^{-1}	THC g kWh^{-1}	CO_2 g kWh^{-1}
142, 144	Gas Oil	Cummins LTA10-R	11.5	0.485	2.32	5.07	819.7
142, 144	SFD	Cummins LTA10-R	10.46	0.66	2.38	4.94	751.8
150,153,155, 156	Gas Oil	Cummins NT855-R5	21.19	0.11	0.84	0.14	651.3
150,153,155, 156	SFD	Cummins NT855-R5	22.39	0.117	0.86	0.18	791.1
158	Gas Oil	Cummins NTA855R3	10.47	0.824	1.23	0.65	656.1
158	SFD	Cummins NTA855R3	9.65	0.624	1.25	0.71	744.2
158	Gas Oil	Perkins 2006-TWH	11.5	0.456	4.45	0.55	941.6
158	SFD	Perkins 2006-TWH	9.65	0.624	1.25	0.71	744.2

The emission levels appear high in comparison to EU Stage IIIB limits however, due to the age of these trains, tracing back to the 1980's, however, the trains are certified compliant as they pre-date all of the emission legislation and are not required to comply with either UIC II or Stage IIIB EU standards. The trains are partially compliant to the UIC I standard of 2002 for PM, CO and THC, however, the trains would fail under Stage IIIB standards, with high levels of NO_x, PM, CO and THC as seen in Table 2.12.

Table 2.12 Exhaust Emissions for gas oil engines from TOC's, compared against legislative standards engines (DieselNet, 2007; DieselNet, 2016; DieselNet, 2018)

	Cummins NTA855R3	UIC I 2002	UIC II	Stage IIIB 2012
NO_x (g kWh^{-1})	10.47	12	6.0	2.0
PM (g kWh^{-1})	0.824	-	0.25	0.025
CO (g kWh^{-1})	1.23	3	0.6	3.5

	Cummins NTA855R3	UIC I 2002	UIC II	Stage IIIB 2012
THC (g kWh^{-1})	0.65	0.8	2.5	0.19

In 2015, Deutsche Bahn conducted GTL trials in Germany on a MTU engine type 8V400041 to monitor exhaust emissions (DB, 2015). The test was conducted using an engine dynamometer test and under the testing regime as per the EN ISO 8178-4 cycle type F. For the engine dyno tests, reductions in NO_x (6%), HC (11%), CO (14%) and PM (28%) over the test cycle using GTL compared to EN590 grade diesel. For individual power modes, there was a significant reduction on idle power using GTL with a 22% reduction in NO_x, 21% reduction in HC, 32% reduction in CO and 54% in smoke number as compared against EN590 grade diesel (DB, 2015).

Table 2.13 MTU Engine specification for Deutsche Bahn GTL trial

Engine	MTU 8V4000 R41
Power	1000 kW
Speed	1800 rpm
Emission classification	UIC II
Fuel consumption	220 g kWh^{-1} or 220 kg h^{-1}
Manufacture year	2000-2004

In 2020, the RSSB established a project, T1186 to determine a revised set of emission factors with units of g km^{-1} for a variety of train traction types as compiled by the NAEI (National Atmospheric Emissions Inventory). This included the 15X, 16X and 17X and 68 train traction types as detailed in Table 2.14 (Grennan-Heaven and Gibbs, 2020b).

Table 2.14 Emission factors in g km^{-1} for a set of UK passenger rail vehicles (Grennan-Heaven and Gibbs, 2020b)

DMU	**150**	**153**	**155**	**158**	**170**
CO (g km^{-1})	1.6	1.6	1.4	2.1	5.5
NO_x (g km^{-1})	5.2	5.2	5.2	3.9	3.9
HC (g km^{-1})	0.3	0.3	0.2	1.1	0.2
NMVOC (g km^{-1})	0.3	0.3	0.2	1	0.2

DMU	150	153	155	158	170
CH_4 (g km^{-1})	0	0	0	0	0
PM_{10} (g km^{-1})	0.08	0.08	0.08	0.52	0.06

2.6.1.2 **Testing in the US**

In the US (United States of America), Graver and Frey have conducted a number of studies on US locomotives including in-passenger locomotive emission measurements for diesel trains (Graver et al., n.d; Graver and Frey, 2013b; Graver and Frey, 2015). One of the research papers by them, measured the individual emissions at each notch for an EMD F59HI locomotive (also known as NC1797) with a PEMS system, over a 173 mi distance. The EMD F59HI contains two engines, a 2 stroke, 12 cylinder, 2240 kW prime mover engine for powering the traction motors, and a 4 stroke, 6-cylinder, 688 kW head end power (HEP) engine for providing electricity for ancillary services on-board the train. The emission tests were conducted as per the US EPA (Environmental Protection Agency) line duty cycle, detailed in 40 CFR Part 1033.515, which involves testing each of the notch settings for approximately 5-10 minutes, as well as testing on pre-test idle for 10-15 mins, as detailed in Table 2.15 (CFR, 2008).

Table 2.15 EPA line duty cycle of 40 CFR Part 1033.515 (CFR, 2008)

Test mode	Notch setting	Time in mode (mins)
Pre-test idle	Lowest idle setting	10 to 15
A	Low idle 2	5 to 10
B	Normal idle	5 to 10
C	Dynamic brake	5 to 10
1	Notch 1	5 to 10
2	Notch 2	5 to 10
3	Notch 3	5 to 10
4	Notch 4	5 to 10
5	Notch 5	5 to 10
6	Notch 6	5 to 10

Test mode	Notch setting	Time in mode (mins)
7	Notch 7	5 to 10
8	Notch 8	10 to 15

The EMD F59HI locomotive train had 9 notch power settings starting with idle, followed by dynamic brake and then a sequential increase of power from notch 1 to notch 8, with notch 8 indicating full power. The averaged, individual notch concentration readings for the species of NO together with the EPA line duty cycle averaged emission factors, are NO_x, HC, CO and PM are presented in Table 2.16 (Graver et al., n.d).

Table 2.16 Exhaust emission concentrations and average cycle emission factors for an EMD F59HI train (Graver et al., n.d)

Notch Position	[NO] (ppm)	NO_x (g kWh^{-1})	HC (g kWh^{-1})	CO (g kWh^{-1})	PM (g kWh^{-1})
0 (idle)	302	-	-	-	-
0 (dynamic braking)	288	-	-	-	-
1	546	-	-	-	-
2	927	-	-	-	-
3	1302	-	-	-	-
4	1384	-	-	-	-
5	1371	-	-	-	-
6	1246	-	-	-	-
7	1282	-	-	-	-
8	1160	-	-	-	-
Average cycle		15.3	3.0	1.1	0.20

2.6.2 Principles of emission measurement instruments

There are a number of different analytical methods which can be used to determine the quantities of the pollutants described previously in the area of exhaust

emissions. Chemiluminescence is the most widely employed technique to determine the levels of NO_x, NO and NO_2. For THC, a FID (Flame Ionisation Detector) is commonly used. For CO and CO_2, NDIR (Non-Dispersive Infrared) is widely utilised. For PM, the gravimetric filter paper method is commonly used. For PN, a CPC (Condensation Particle Counter) can be utilised. Other instruments used for PN in the commercial sector include, SMPS (Scanning Mobility Particle Sizer spectrometer) and ELPI (Electrical Low Pressure Impactor). The FTIR (Fourier Transform Infrared Spectroscopy) is an alternative method to determine the concentrations of CO, CO_2, NO, NO_X and many more gases. For the gaseous pollutants of NO, NO_2, NO_x, THC and CO, concentrations in parts per million (ppm) are measured whereas CO_2 is measured as volume percentages. The previously described pollutant measurement techniques are used coupled together as part of an integrated system for vehicle emission testing. A dynamometer or dyno is typically used as part of vehicle emission testing except for PEMS testing and “is a device by means of which energy or work done by a prime mover can be measured” (SHARMA and PUROHIT, 2006).

Vehicle emission testing is conducted by one of three methods using:

1. Engine dynamometer coupled to a vehicle engine
2. Chassis dynamometer coupled to a vehicle with wheels
3. PEMS connected to a moving vehicle

If the vehicle is stationary, then a dynamometer is used to measure the amount of torque exerted on the engine by applying frictional resistance to either the engine crankshaft in the case of the engine dynamometer or the vehicle’s tyre wheels mounted on metal rollers in the case of the chassis dynamometer. The engine dynamometer requires the engine to be removed from the vehicle and connected as a standalone unit to a dynamometer and can be conducted on any engine from car engines, to rail engines. The chassis dynamometer or rolling-road dynamometer keeps the engine within the vehicle, and mounts the vehicle on top of metal rollers positioned under each of the vehicle’s circular tyres, to simulate a road environment. This type of test is primarily used for road transportation testing. In the past however, the origins of the chassis dynamometer test trace back to first use in the rail sector with steam locomotive trains in which: “multiple-axle units with large eddy-current dynamometers connected to each driven axle fitted with rollers with rail-line profiles”. A PEMS test is the third option for vehicle emission testing and does not require a dynamometer, since the test is conducted with the vehicle in motion,

and so the load is inherently applied to the engine though motion. Dynamometer or PEMS tests with movement, allow the gaseous pollutant concentrations readings to be converted into the legislative limits, which for the case of heavy duty vehicles is rated in g kWh^{-1} within the EU and g $BHP.h^{-1}$ for the US.

2.6.2.1 NO_x Chemiluminescence Analyser (CLA)

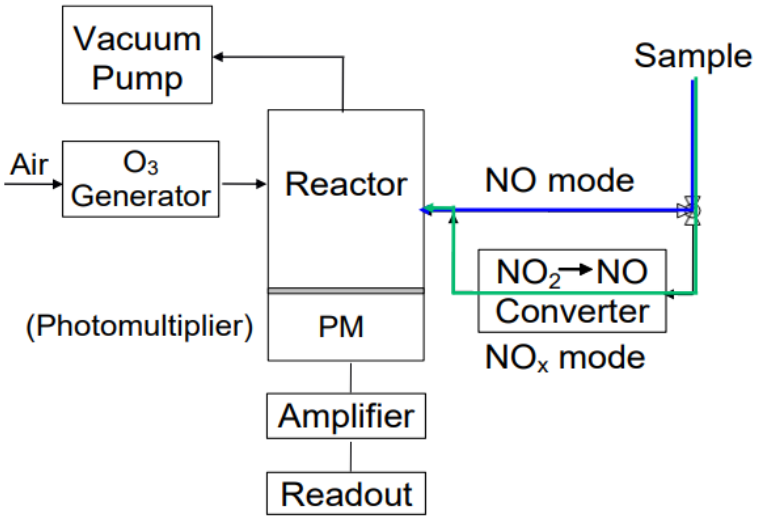


Figure 2.7 Chemiluminescence Process (Ross, 2018)

NO_x Chemiluminescence involves reacting NO with Ozone to an excited state as shown in equation 2.18.

$$NO + O_3 \rightarrow NO_2^* + O_2 \quad (2.18)$$

The excited NO_2^* returns to the ground state emitting a wavelength of hv_1, as shown in equation 2.19.

$$NO_2^* \rightarrow NO_2 + hv_1 \quad (2.19)$$

The emitted light, hv_1, is measured with a photomultiplier. This measurement is proportional to the mass flow rate of NO within the reactor chamber. From this the amount of NO can be determined. This process is illustrated in Figure 2.7.

To determine the amount of NO_x, the reactor is put into NO_x mode, in which the NO_2 component in the NO_x inlet stream is run under a Cu catalyst at 700°C, as shown in equation 2.20.

$$2\ NO_2 \rightarrow 2\ NO + O_2 \quad (2.20)$$

This acts to break down the NO_2 into NO and O_2. Following this, the NO can be excited to NO_2^* as in equation 2.18. This will produce a wavelength of hv_2, as per

equation 2.21 which can be used in a photomultiplier to give the quantity of NO_x (Ross, 2018).

$$NO_2^* \rightarrow NO_2 + hv_2 \quad (2.21)$$

In order to determine the quantity of NO_2, the concentration of NO and NO_x must be determined. The quantity of NO_2 is found by the difference between NO_x and NO as shown in equation 2.22.

$$[NO_2] = [NO_x] - [NO] \quad (2.22)$$

2.6.2.2 **Non-Dispersive Infrared (NDIR)**

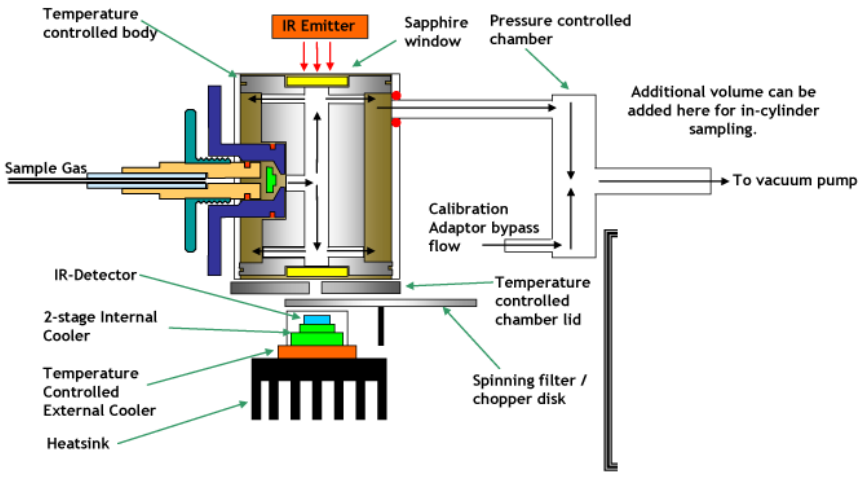


Figure 2.8 Non-dispersive infrared process (Cambustion, n.d-b)

Non-dispersive infrared is a technique used to determine to measure the concentration of gases. Its' primary use industrially is in CO and CO_2 concentration measurement, however, it can also be used to measure CH_4 (methane), C_2H_2 (acetylene) and HCl (hydrogen chloride) (Ross, 2018). As shown in Figure 2.8, NDIR operates by shining an infrared beam through a splitter to a sample and measuring the quantity of infrared absorbed at specific wavelengths unique to the analyte in the sample mix. There are no prisms involved in NDIR, in which the infrared passes through the sample gas directly. A detector compares the absorbance of the analyte and subtracts it from a reference gas of typically nitrogen. This change in absorbance is proportional to the concentration of the analyte in the sample (RAE, n.d).

2.6.2.3 **Flame Ionisation Detector (FID)**

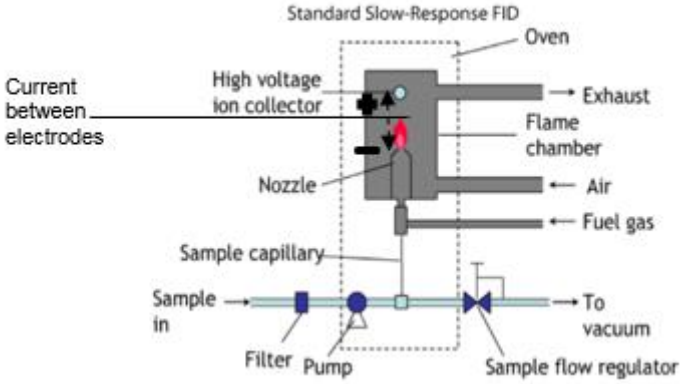


Figure 2.9 Flame ionisation detector operating principle (Cambustion, n.d-a)

Flame ionisation detection is a technique used to measure the amount of total hydrocarbons (THC) in a gas sample. Typically it is utilised in the automotive engine sectors, to determine the amount of THC in the engine exhaust. It operates via burning a small amount of the sample exhaust gas in a small flame of hydrogen. This results in the formation of ions, arising due to the burning of hydrocarbons. The ions are then detected via high voltage ion collector, as seen in Figure 2.9. The current applied between the collector electrode and the electrode near the nozzle, is proportional to the concentration of hydrocarbons in the sample (Cambustion, n.d-a). This unit does not measure CO, CO_2, or NO_x (Ross, 2018).

2.6.2.4 Particulate Matter (PM) measurement for automotive exhaust measurement

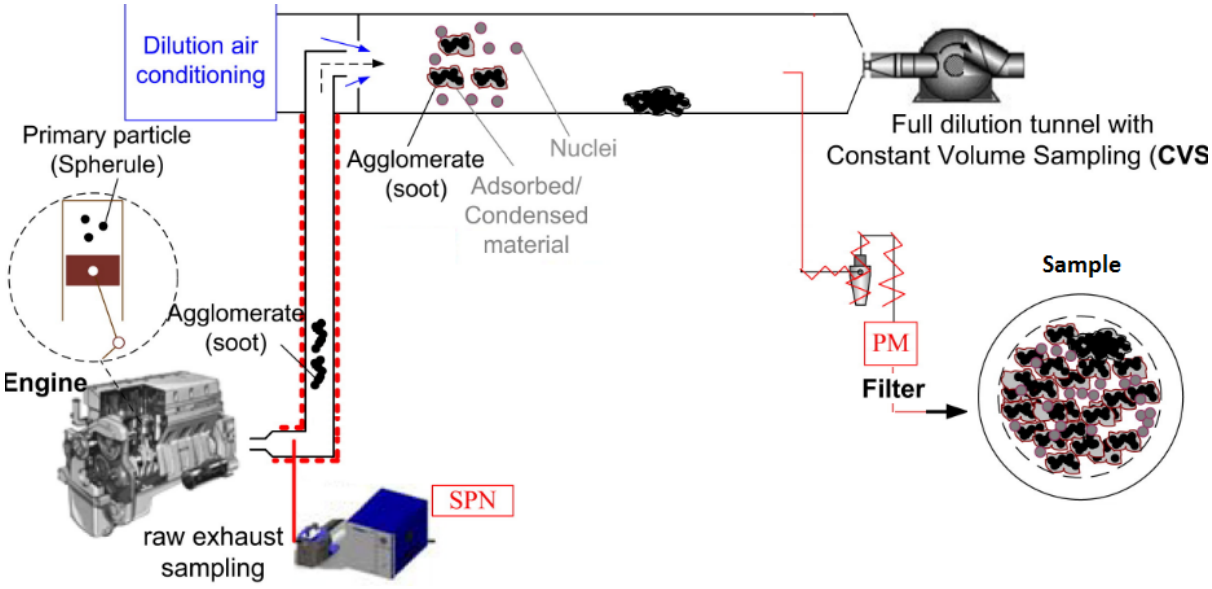


Figure 2.10 Particulate matter sampling using a full-flow dilution tunnel (Giechaskiel et al., 2014)

To sample, particulate matter (PM) for automotive engines, there is a standard regulated method used in the commercial sector. This involves having the exhaust sample diluted using a CVS (Constant Volume Sampling) full-flow dilution tunnel or a partial flow dilution system, as seen in Figure 2.10. For a full-flow dilution tunnel system, a sample of exhaust gas, is taken from the engine and then diluted using ambient air to reduce the temperature to 47°C. The diluted exhaust gas temperature must be set “at the filter face at 47°C ± 5°C” (Burtscher et al., 2016). The cooled exhaust then enters a cyclone to remove large solid particles from the diluted exhaust. Following this, the exhaust passes through a single 47 mm HEPA (High Efficiency Particulate Air) filter, typically made of pure PTFE (polytetrafluoroethylene) “to protect the surface from chemical reactions” (Giechaskiel et al., 2014). The PTFE filter should be “circular with an overall diameter of 46.50 ± 0.6 mm and an exposed diameter of 38 mm”, as well an overall thickness of 40 ± 20 µm (GPO, 2010). The solid particles are collected on the PTFE filter and the filter can then be weighed. The filter weight can be subtracted from the blank filter weight to determine the mass of particulates on the filter paper.

2.6.2.5 Particle Number (PN) Measurement using a Condensation Particle Counter (CPC)

A condensation particle counter operates by counting the number of particles to determine a particle concentration. Air containing particles are passed through a porous medium which is in contact with a working fluid e.g. butanol, as seen in Figure 2.11 (UoM). The air becomes saturated and is then condensed to become supersaturated. This results in some of the particles turning into droplets. The droplets are focussed through a nozzle, after which a laser beam is passed through the concentrated droplets and counts the number of droplets (TSI, 2014).

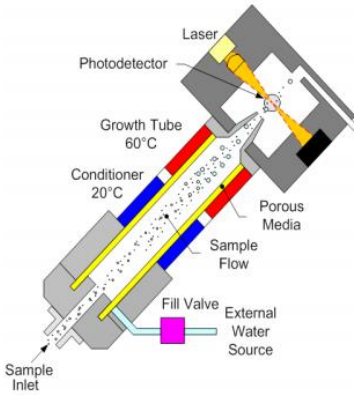


Figure 2.11 CPC operating principle (TSI, 2014)

2.6.3 Diesel Exhaust Emission Reduction

These are a number of systems which can be retrofitted to the existing diesel engines to reduce the quantity of pollutants such as NO_x and PM. There are three main technologies for exhaust aftertreatment: Selective Catalytic Reduction (SCR), a Diesel Oxidation Catalyst (DOC) and a Diesel Particulate Filter (DPF).

2.6.3.1 SCR (Selective Catalytic Reduction)

SCR reduces the amount of nitrogen oxides in the diesel exhaust by reacting the NO and NO_2 in the exhaust stream with a diluted urea-water mixture, known as Adblue® with a composition of typically 32.5 wt.% mass urea and 67.5 wt.% demineralised water. The composition specification is outlined in ISO 22241-1 with a range of urea allowed between 31.8-33.2 %m/m urea (ISO, 2006). The urea decomposes into ammonia (NH_3) during atomisation in the engine, in which the urea solution is dehydrated to a liquid or gaseous form of urea as seen in equation 2.23.

The urea then decomposes into ammonia and isocyanic acid (HNCO) as seen in equation 2.24 (Yim et al., 2004). The HNCO reacts with water vapour to produce further gaseous ammonia and CO_2 shown in equation 2.25. The ammonia then reacts with the NO and NO_2 gases, in a number of parallel reactions as shown through equations 2.26-2.30 (Majewski, 2005).

$$NH_2\text{-}CO\text{-}NH_2\ (aq.) \rightarrow NH_2\text{-}CO\text{-}NH_2\ (l \text{ or } g) + xH_2O\ (g) \quad (2.23)$$

$$NH_2\text{-}CO\text{-}NH_2\ (l \text{ or } g) \rightarrow NH_3\ (g) + HNCO\ (g) \quad (2.24)$$

$$HNCO\ (g) + xH_2O\ (g) \rightarrow NH_3\ (g) + CO_2 \quad (2.25)$$

$$6NO + 4NH_3 + O_2 \rightarrow 5N_2 + 6H_2O \quad (2.26)$$

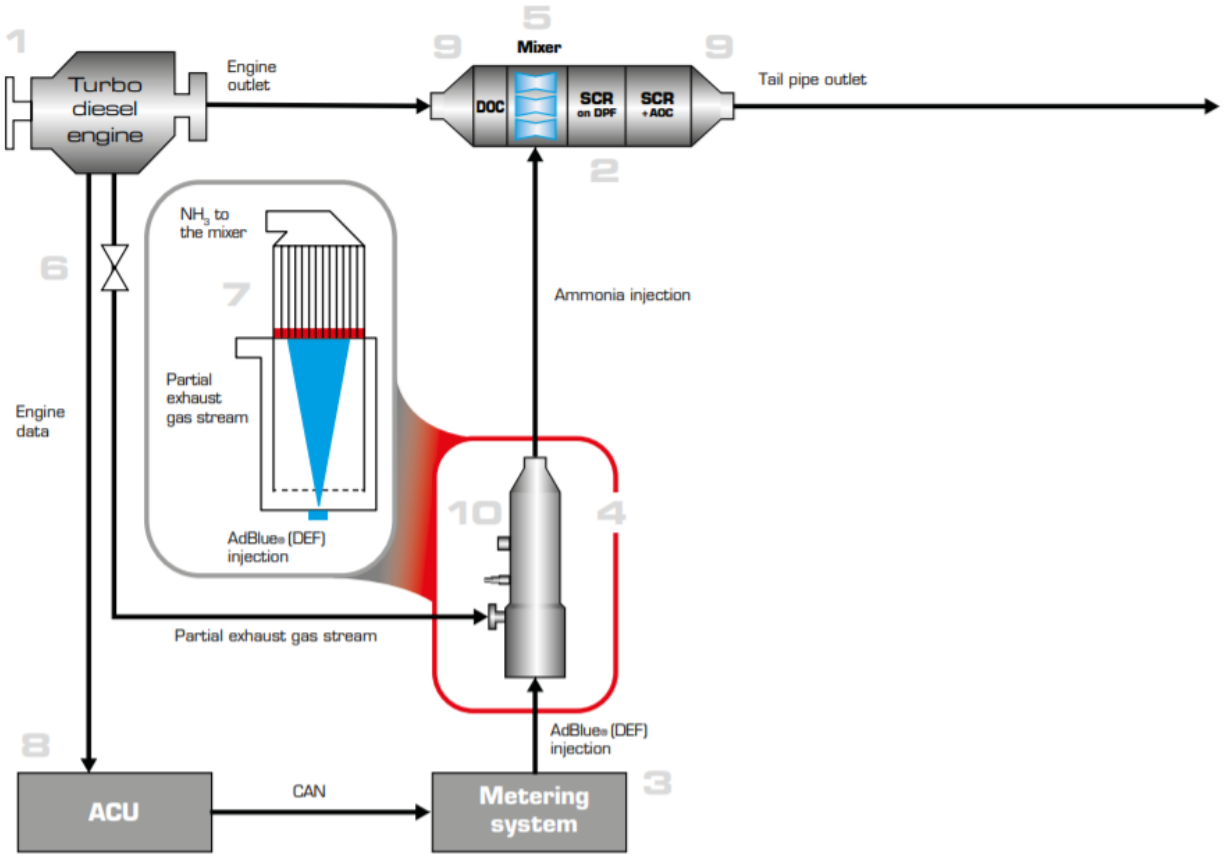
$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \quad (2.27)$$

$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O \quad (2.28)$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O \quad (2.29)$$

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O \quad (2.30)$$

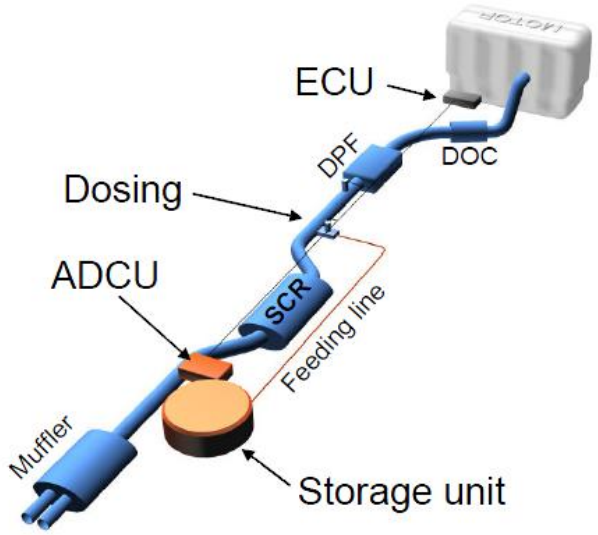
The operating temperature for the SCR system is typically in the 200-450°C for liquid urea injection. However, this can lead to the SCR system being inactive at lower engine power settings such as in idle, as noted in the RSSB report, T1187 with SCR systems operating “at medium and high exhaust temperatures and not at low exhaust temperatures that usually correlate with low power conditions including idle” (Grennan-Heaven and Gibbs, 2020d). There is however, a solution for low temperature SCR operation with retrofit suppliers developing unique modifications to the SCR system for operation at temperatures as low as 120°C, to remove exhaust NO_x at this temperature. One such retrofit supplier, Baumot achieves low temperature operation by converting the liquid urea into gaseous ammonia before injection into the exhaust stream, commercially marketed as a ‘BNO_x’ system (Hayes, 2019).



1 Diesel Engine 2 Exhaust gas treatment system 3 Metering system 4 Ammonia generator 5 Mixer 6 Turbocharger 7 Heated catalyst 8 Exhaust gas control unit 9 NO_x sensor 10 Temperature sensor on BNO_x generator

Figure 2.12 Baumot NO_x system (Baumot, 2017)

Another retrofit supplier, Amminex Emissions also allows low temperature operability at 140°C by replacing the liquid urea injection with ‘ammonia absorbed into a complex salt of $Mg(NH_3)6Cl_2$, commercially known ASDS (Ammonia Storage & Delivery System) (Hayes, 2019; Banner, 2018). The ammonia is stored in solid form in AdAmmine within cartridges which need to be replaced periodically. The cartridges are heated to 55°C, which releases the ammonia gas, with a power penalty of 150 kW (Johannessen et al., 2014; Banner, 2018).



ADCU Ammonia dosing control unit ECU Engine control unit

Figure 2.13 Amminex Emissions ASDS with SCR (Congress, 2018)

It is unclear however, if within the rail sector, the new build EU Stage IIIB trains have used this low temperature SCR technology within their trains, since their trains comply with the numerical limits for each of the pollutants as per the EU Stage IIIB legislation using the ISO 8178:C1 test cycle. In addition, there is an issue with how the ISO 8178:C1 test is conducted, with a very low percentage of test in the low-idle mode, with 15% of the test weighting, in contrast to the older test regime of ISO 8178:F of 2002 which had a much higher low-idle test weighting at 60%, which as noted in the RSSB T1187 report makes it “easier to comply with IIIB with C1 test cycle” for train operating companies, and so providing a poor incentive for train operator companies to mitigate NO_x at low exhaust temperatures (Grennan-Heaven and Gibbs, 2020a).

2.6.3.2 **DOC (Diesel Oxidation Catalyst)**

A DOC converts carbon monoxide to carbon dioxide and hydrocarbons to carbon dioxide and water vapour, as shown in equation 2.31. It can also oxidise some of the particulate matter (up to 20%) to water and carbon dioxide. However, it undesirably oxidises NO to NO_2 as seen in equation 2.32 (AirFlow, n.d). Most DOC’s are made from platinum with different configurations of the catalyst dependent on the manufacturer (Majewski, 2018).

$$HC + CO + 2O_2 \rightarrow 2CO_2 + H_2O \quad (2.31)$$

$$2NO + O_2 \rightarrow 2NO_2 \quad (2.32)$$

2.6.3.3 **DPF (Diesel Particulate Filter)**

A DPF traps particulate matter of a certain particle size, with a removal efficiency of up to 99% of soot (NETT, n.d). The most common type of DPF is the wall-flow filter. The wall-flow filter has a honeycomb structure which removes the PM by filtration. The PM becomes trapped on the walls as a soot cake, and the purified exhaust stream flows through the channels of the honeycomb structure. The soot cake that agglomerates on the walls is burnt off, to prevent the DPF from getting blocked, and this is known as the regeneration stage of the DPF. The DPF also contains a catalytic coating which reduces the CO and HC, to CO_2 and H_2O, however, it also converts some of the NO to NO_2, an undesired pollutant. Therefore the DPF has to be used in parallel with another aftertreatment system such as SCR, to convert the NO_2 into N_2 (umicore; Schäffner et al., 2011).

2.6.3.4 **Aftertreatment combination systems**

The aftertreatment technologies can be used in conjunction with each other, with a DOC-SCR configuration possible, as well as a DOC-DPF system, known as a CRT (continuously regenerating trap) system (NETT; NETT). A CRT system consists of a combined DOC and a DPF system. The DOC part of the system oxidises NO to NO_2 and also oxidises HC and CO to CO_2 and H_2O as seen previously in equations 2.31 and 2.32. The NO_2 then regenerates the particulate filter allowing operation at low exhaust gas temperatures of 250-275 °C (Ian, 2006a).

2.6.3.5 **Previous studies on aftertreatment systems in the UK rail sector**

The RSSB in 2006 conducted tests to trial the performance of aftertreatment system retrofitted to a train. This test involved using a CRT retrofit system on a Cummins NTA855R3 engines with the emission measurements with the new system given in Table 2.17 given in units of g kWh^{-1}. Little information is available regarding the test procedure however, it can be assumed that the tests were conducted as per the ISO 8178 Part 4, Test Duty Cycle F. The CRT tests showed reductions in all pollutants, as seen in Table 2.18. The Cummins NTA855R3 engine tested is utilised by Northern Rail in its' 158 DMU. The relevance of this to this project is that it illustrates that lower exhaust emissions are possible by incorporating aftertreatment

systems into existing trains, as seen in Table 2.18. This is one type of aftertreatment that Northern Rail could look to incorporate into its' DMU fleet, and thereby creating better conditions for air quality within their maintenance depot facilities, via reductions in DMU exhaust emissions at the point of source.

Table 2.17 Cummins NTA855R3 engine test with CRT using SFD fuel (Ian, 2006a)

Train Model	**Engine**	**NO_x g kWh^{-1}**	**PM g kWh^{-1}**	**CO g kWh^{-1}**	**THC g kWh^{-1}**	**CO_2 g kWh^{-1}**
158	Cummins NTA855R3	9.37	0.0093	0.14	0.03	604.8

Table 2.18 Percentage reduction in rail engine emissions using a CRT system with SFD fuel on a Cummins NTA855R3 engine

Pollutant**s from Cummins NTA855R3**	**% Reduction with CRT**
NO_x	↓ 3.4%
PM	↓ 98.5%
CO	↓ 89.2%
THC	↓ 95.6%
CO_2	↓ 98.5%

2.7 Air quality monitoring

The effects of releasing diesel exhaust emissions from trains without engine aftertreatment systems into the atmosphere, are higher quantities of primary pollutants entering the atmosphere and the formation of secondary pollutants such as NO_2. This can negatively affect the air quality, which in the context of this project, are in particular relevance to the areas both inside and outside of the 4 railway depots considered in this project. The Neville Hill railway depot in Leeds and the Heaton depot in Newcastle are located adjacent to residential areas, so there could be an impact on the local air quality, due to the DMU emissions' arising from trains without aftertreatment technology. A literature survey will hence be presented which

summarises the impact on local air quality in areas surrounding other railway stations and railway depots around the world.

In the UK, a number of authors have investigated the air quality within train stations and this is of particular relevance to this project as it provides a reference point for the railway depot and station measurements of this project. Chong et al. investigated the concentrations of pollutants of PM and NO_x at platform level (Uven et al., 2015). This is relevant to this project as ambient air quality measurements will be conducted at platform level in the four railway depots operated by Northern Rail. By having this reference data from a variety of sources, in particular the work by Chong et al. at London Paddington, Hickman et al. at Birmingham New Street and a study from King's College London by Fuller and Green, typical data of NO_2 can be used to compare against for the proposed NO_2 work planned for the 4 railways depots planned for as part of this project (Uven et al., 2015; Hickman et al., 2018a; Fuller et al., 2014; Green et al., 2019).

2.7.1 Air quality monitoring techniques

There are two methods for monitoring atmospheric pollutants, these are batch monitoring and continuous monitoring. Within batch monitoring, pollutants are monitored over a single measurement within a fixed time frame. Typically these are used in laboratory analysis (Williams, 2018).

2.7.1.1 Batch monitoring - Diffusion Tubes

In this study, with NO_2, a key pollutant of interest for this study, diffusion tubes are the most common batch monitoring method for monitoring NO_2. Diffusion tubes, picture in Figure 2.14, are a type of air quality monitoring device used to monitor ambient air quality. They are appropriate as a simple measurement device for monitoring air quality with a low unit cost offering flexible use over a large area and long-term monitoring (DEFRA, 2017a).

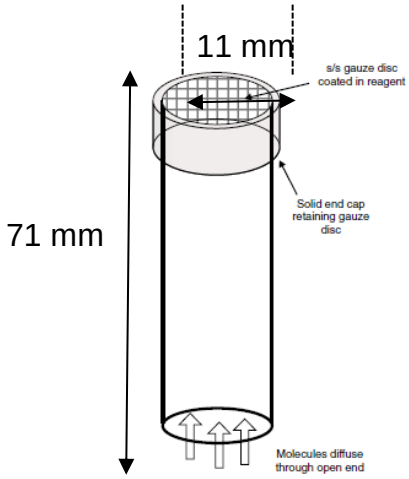


Figure 2.14 Typical Diffusion tube (Colls, 2002b)

Diffusion tubes are cylindrical devices which contain a disc coated with a TEA (triethanolamine) absorbent to react with the monitored gas. TEA (Triethanolamine) is used as a coating agent since it has “the capacity to remove between 90-100% of the NO_2 from the air sampled, using sequential sampling” (Cape, 2005). It is recommended by the LAQM (Local Air Quality Management), prior to sampling that unexposed tubes be stored “in a sealed plastic container in a fridge or if in area without a fridge, then the unexposed tubes should be stored in a cool dark place without temperature fluctuations” (AEA, 2008a). Both options are equally valid. During operation, the bottom capped white end is removed and the tube is left in the sample point location with the red end pointing upwards, as seen in Figure 2.15 (DEFRA, 2017a). Post exposure, the diffusion tubes should be stored in a fridge until analysis is conducted.

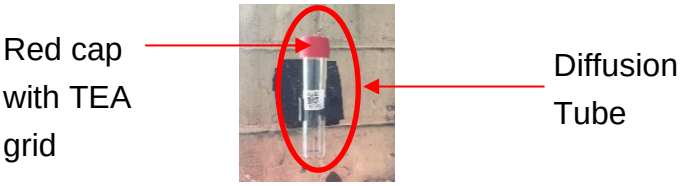


Figure 2.15 Diffusion tube with the bottom cap removed for NO_2 sampling

The principle behind diffusion tubes is molecular diffusion, in which air components from the ambient air enter the opened end of the diffusion tube, moving from an area of high concentration to an area of low concentration within the tube as seen in Figure 2.16, in which the air compounds agglomerate on the absorbent at the end of the tube. There is a small grid on the end of the absorbent tube, inside of the red cap. The grid is typically 4x4 mm. The sample is left to accumulate on this grid for a minimum period of two weeks with a maximum limit of four weeks. Once the sample is ready for analysis, the tube is sealed with the original white cap for laboratory analysis as per DEFRA (Department for Environment, Food and Rural

Affairs) guidance within AEA/ENV/R/2504 (AEA, 2008b). During laboratory analysis, a number of reagents are added to the diffusion tube and then agitated, to produce a nitrite compound. A small sample of this reagent mixture from the diffusion tube is taken for colorimetry analysis using a UV-visible dual beam spectrophotometer to measure the absorbance of the nitrite compound. Using a calibration curve, the nitrite concentration can be determined from the absorbance of the sample of the colorimetry analysis. Using Equation 2.33, the NO_2 concentration at 293K can be determined from the nitrite concentration.

$$[NO_2]_{293K} = \frac{[NO_2]^- \text{ x } V_e}{\frac{D_{12}\, XS_t}{l} \times t} \text{ x } \frac{284}{293} \quad (2.33)$$

where $[NO_2]_{293K}$ is the concentration of NO_2 at 293K, $[NO_2]^-$ is the nitrite concentration, V_e is the extraction volume, D_{12} is the Diffusion coefficient, XS_t is the cross sectional area of tube, l is the length of the diffusion tube.

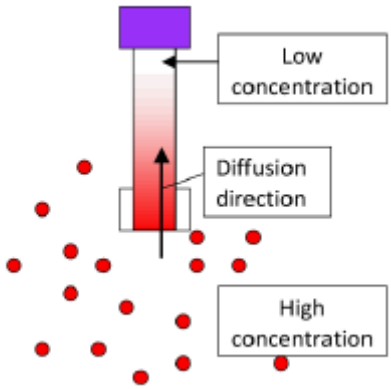


Figure 2.16 Movement of bulk molecules from a high to low concentration in a diffusion tube (Gradko, 2017a)

There are number of advantages to using diffusion tubes in that they require no external power, are low cost, can be used over a wide area and offer a long term monitoring solution (2-4 wks). The disadvantages of using these are the high level of bias, in particular with using the 50% TEA tubes in acetone. In addition, diffusion tubes offer a poor time resolution of measurement as by design they output a single, averaged concentration volume over a monthly period. The typical specification of the diffusion tube is detailed in Table 2.19.

Table 2.19 Typical specifications for a diffusion tube (Gradko, 2017c)

Parameter	Value
Type	50% TEA/Acetone
Tube Length	71mm

Parameter	Value
Internal diameter	11 mm
Recommended Exposure Period (wk.)	2-4
Air velocity, <10% wind speed (ms^{-1})	1-4.5
Shelf Life (wk.)	6
Limit of detection	Total NO_x <3 µg m^{-3} for 4 wk
Relevant Standards	BS EN 13528 Parts 1-3: 2002/3
Desorption Eff.	0.98
Storage	Dark, cool environment, T= 5-10°C
Cost per tube	£5.95 + VAT
Accessories	Clip to Hold £1.20 + VAT (per tube)

As seen in Table 2.20, the low cost nature of the diffusion tube is illustrated, with the cheapest tube available from Gradko £6 (ex. VAT) retail price per tube. The other diffusion tube supplier, Enviro Technology retails the same tubes at almost double the cost, however, the reason for this higher price when compared against Gradko is unknown. Additional information on the precision and bias of the diffusion tube are provided in Table 2.21 and Table 2.22, in which it can be seen that the diffusion suffer from a variable bias and a precision level which can be poor.

Table 2.20 Typical cost of a diffusion tube (Gradko, 2017b; Safety, 2017; John, 2017)

Company	Unit Cost(£/NO_2 tube)	Typical sale	Cost (Single Tube Holder)	Min Sale Cost (10 tubes)
Gradko	£5.95	10 tubes	£1.20	£60.70
Enviro Technology	£11.90	10 tubes	£3.30	£170

2.7.1.1.1 Precision

An example of the typical precision for diffusion tubes are shown in Table 2.21 based on historic data from the LAQM (DEFRA, 2016)

Table 2.21 Typical levels of precision for diffusion tubes (DEFRA, 2016)

Diffusion Tube	Bias (%)	Precision
20% TEA in water	-22 to +46.4	Good to Poor
50% TEA in acetone	-22 to +88.1%	Good to Poor

2.7.1.1.2 Bias

An example of the typical bias range for diffusion tubes are shown in Table 2.22 based on historic data from the LAQM (LAQM, 2021b).

Table 2.22 Levels of bias for diffusion tubes which are 20% TEA in water (DEFRA, 2016)

COMPANY	Bias (%)	Precision	Diffusion Tube Mean Conc. (µg/m^3)
Aberdeen Scientific Services	-6.5 to +31.4%	Good	21 to 79
ESG Didcot	-0.1 to 34.6%	Good	32 to 104
Gradko	-22 to +46.4	Good	4 to 99

The uncertainty for a typical diffusion tube measurement was found by Bush et al. to be ±24-38%, with the annual averaged uncertainty for a diffusion tube determined by Bush et al. ±10-18% (Bush et al., 2001).

2.7.1.1.3 Reducing diffusion tube uncertainty

The Joint Research Council (JRC) and other authors have investigated a number of options to modify the diffusion tubes to reduce uncertainty. These include:

- fitting an amorphous polyethylene (PE) filter to exposed end of the tube to reduce wind speed interferences and humidity effects, which reduced the expanded uncertainty to ±10% from ±33% (Martin et al., 2014)
- fitting an enclosure around the diffusion tube to reduce wind speed interferences, which reduced the uncertainty to <25% (HAFKENSCHEID et al., 2009) (ISO 13752)

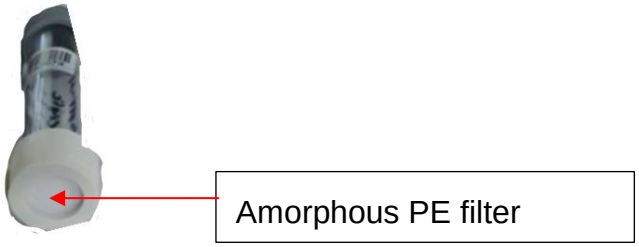


Figure 2.17 Modification of diffusion tube with an amorphous polyethylene filter, image reproduced from Martin (Martin et al., 2014)

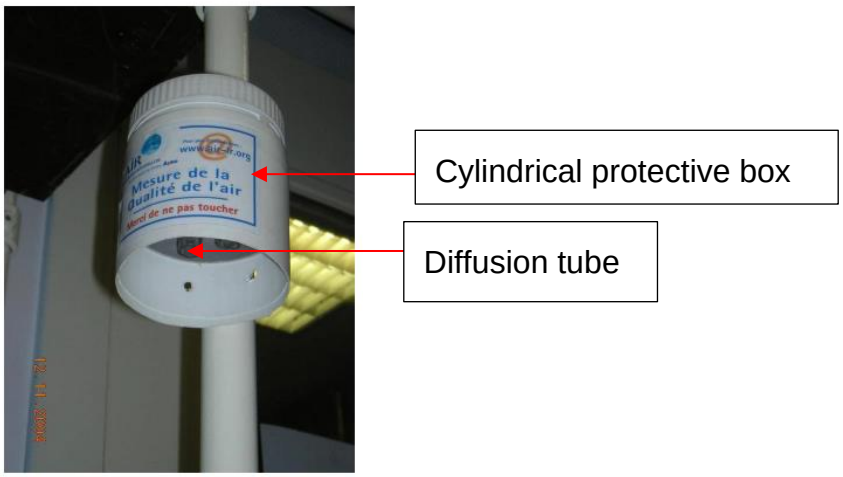


Figure 2.18 Cylindrical protective box for diffusion tube, image reproduced from JRC (HAFKENSCHEID et al., 2009)

2.7.2 Automatic monitoring

For PM, there are 2 methods in the UK most commonly used for ambient air quality monitoring, which are TEOM (Tapered Element Oscillating Microscope) and BAM (Beta Attenuation Monitoring). These are equivalent to the manual gravimetric reference method set out by the EU in EN 12341:2004 which 'samples the particulate matter on filter and weighs them by means of a balance'(BS, 2014). However, the equivalent methods are not themselves reference methods (EU, 2022). In the UK, DEFRA in conjunction with the UK's EA (Environmental Agency) have put together a list of TEOM and BAM instruments, which are appropriate for PM monitoring and have MCERTS certification. The list includes 22 instruments, and includes Thermo Partisol 2025, Thermo TEOM 1400, GRIMM EDM180, as well as many others (DEFRA, 2022). MCERTS certification also known as the MCERTS scheme is a certification method which ensures that the instrument, in this case for PM, is appropriate for use for monitoring, and is also equivalent to reference method set by the EU, within 2008/50/EC/Annex VI EC (DEFRA, 2012; EU, 2008b). For NO_2,

a chemilumescence analyser is the method used for ambient air quality monitoring of NO_2 in the UK and is a reference method as outlined in EN 14211:2012 (BS, 2012).

2.7.3 Tapered Element Oscillating Microbalance (TEOM)

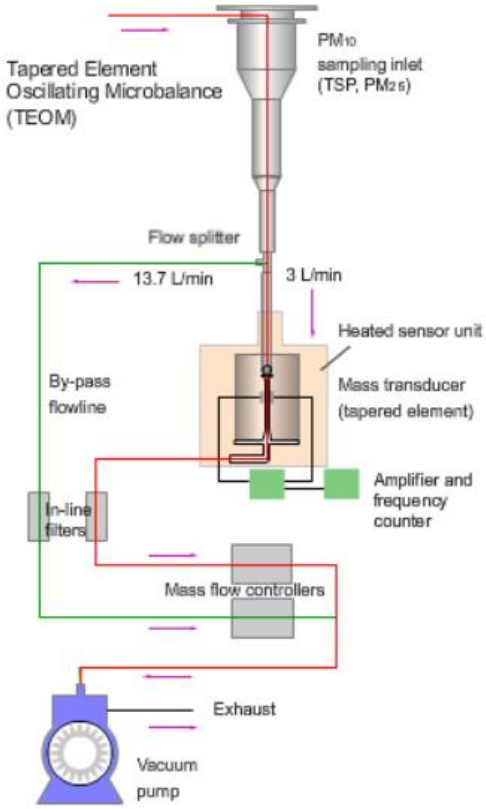


Figure 2.19 Tapered element oscillating microbalance process (QLD, 2017)

In a TEOM, a sample is drawn through a filter on top of an oscillating glass tube in an applied electric field. As the particles pass through the glass the tubes, the oscillation reduces and particles accumulates on the filter. The resonant frequency decreases as the filter collects particles. The change in resonant frequency can be used to determine the mass of the particles. The change in resonant frequency is proportional to the mass of particles. The TEOM however, does have a drawback, as it loses semi-volatile material when operating at its normal conditions of 50°C ((SNC-Lavalin), 2006). To account for this DEFRA, have recommended to use a volatile correction model (VCM), which utilises data from nearby TEOM-FDMS (Filter Dynamics Measurement System) units, which are within 200 km of the TEOM (KCL and DEFRA, 2012). A TEOM-FDMS is a modified version of a TEOM, and accounts for this lost semi-volatile material. Different from a standard TEOM, it first dries the sample, and then uses a switching value to alternate between a base and purge

mode every six minutes (DEFRA; and AEA;, 2008). The change in mass between the two modes is measured by a microbalance (KCL, 2005). The TEOM-FDMS operates at a lower temperature of 30°C (DEFRA; and AEA;, 2008).

2.7.4 Beta Attenuation Monitor (BAM)

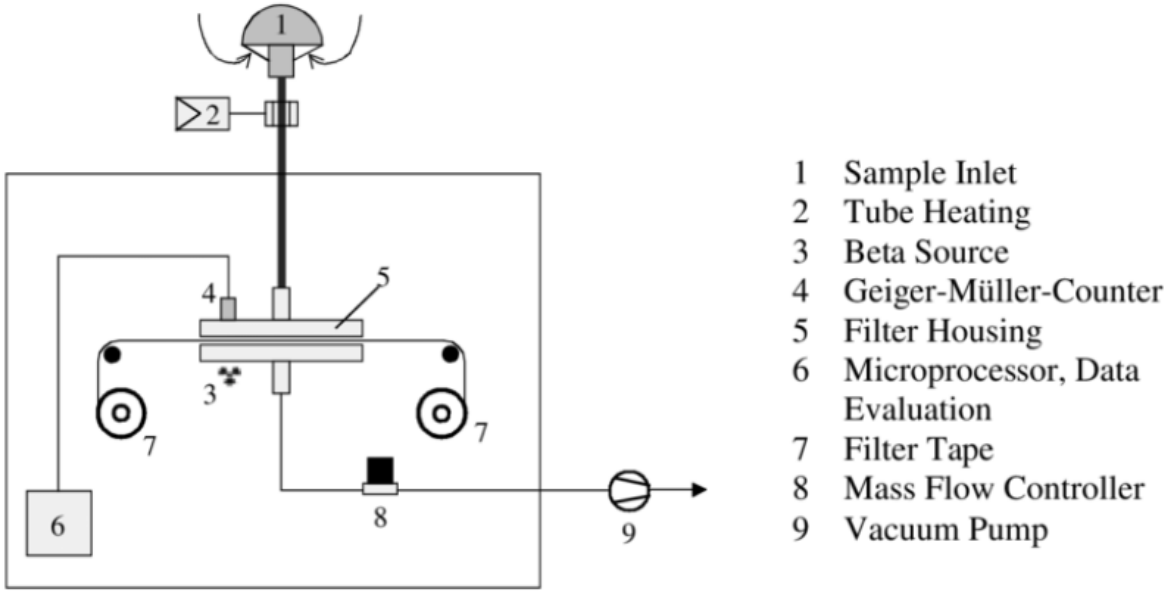


Figure 2.20 Beta Attenuation Monitor process (Asbach, 2013)

In a BAM, a sample of particles is drawn from the air onto a spool of tape. A Carbon-14 element placed above the tape, emits beta particles, which attenuates the tape with the particles. The change in resonance before the pre and post sampled filter tape, is used to determine the mass of particles. The resonance change is proportional to the mass of particles in the air sampled.

2.7.5 Air quality monitoring in the proximity of train stations

Chong et al. investigated the air quality of the UK train station, London Paddington (Chong et al., 2015). In this work, PM and NO_x concentrations were observed at five locations within the station, platforms 1 and 8, the station centre, and by the roadside of the station. The averaged $PM_{2.5}$ level was found to be 16 µg m^{-3} per hour, with NO_2 averaged hourly values of 73 ppb. PM was measured using a photometer and a CPC was utilised to observe the particle number concentrations. NO_x was measured used a chemiluminescence analyser (CLA) (Uven et al., 2015). Building on the work of Chong et al., Hickman et al. investigated the ambient air

quality at Birmingham New Street train station over the 12 station platforms and areas surrounding the station (Hickman et al., 2018a). NO_2 concentrations of 407 µg m^{-3} were observed over a 2 month test period between Dec 2016 and Jan 2017 on platforms 10 and 11 of the station using a Horiba APNA-370. These platforms were chosen due to the high traffic of diesel trains on these two platforms. In addition, during this period $PM_{2.5}$ was observed at 42 µg m^{-3} and PM_{10} at 53 µg m^{-3} (Hickman et al., 2018a). Diffusion tubes were used to observe the spatial variations in NO_2 concentration with measurements taken at 3 locations, the 2 platform ends and platform centre spaced at 50m, on each of the 12 platforms during two week periods, 18th Oct 16 – 01st Nov 16 and 01st Nov 16 – 15th Nov 16 as seen in Table 2.23.

For the diffusion tubes, the 2-week concentrations of NO_2 ranged between 178 µg m^{-3} at the eastern end of platform 6 during the first period, to 508 µg m^{-3} in the centre of platform 2 during the second period, within the station. It is interesting to note that although the author chose to carry out real-time monitoring on Platforms 10 and 11, due to the perceived high traffic of diesel trains, Platform 2 may have been a better option for real-time monitoring with levels of 437 µg m^{-3} and 508 µg m^{-3} observed during the 1st and 2nd diffusion tube testing periods, which was higher than the other platforms (Hickman et al., 2018a). Black carbon and CO_2 were also monitored during Dec 2016 and Jan 2017, with an Aethalometer AE33 used for black carbon measurements and CozIR CO_2 sensors used for the latter measurement. Concentrations of 20 µg m^{-3} black carbon and 658 ppm CO_2 were observed at the centre of platforms 10 and 11. Within the station, CO_2 was used as a tracker for the other pollutants such as NO_2, with a ventilation system in place to adjust the extraction air flow in the event of high CO_2 concentrations. However, the work by Hickman et al. showed a weak correlation between CO_2 and NO_2, with high CO_2 concentrations not necessarily corresponding to high levels of NO_2, a R^2 value of 0.36 was calculated between CO_2 and NO_2.

Table 2.23 Fortnightly diffusion tube average NO_2 measurements at Birmingham New Street station for two periods, period 1: 17th Oct 16 – 01st Nov 16 and period 2: 01st Nov 16 – 15th Nov 16 (Hickman et al., 2018a)

	Period 1: 17/10/16-01/11/16			**Period 2: 01/11/16-15/11/16**		
	West end of the station	**Centre of the station**	**East end of the station**	**West end of station**	**Centre of the station**	**East end of the station**
Platform	**NO_2 (µg m^{-3})**	**NO_2 (µg m^{-3})**	**NO_2 (µg m^{-3})**	**NO_2 (µg m^{-3})**	**NO_2 (µg m^{-3})**	**NO_2 (µg m^{-3})**
1	276	440	250	285	464	384

	Period 1: 17/10/16-01/11/16			Period 2: 01/11/16-15/11/16		
	West end of the station	Centre of the station	East end of the station	West end of station	Centre of the station	East end of the station
Platform	NO_2 ($\mu g\ m^{-3}$)	NO_2 ($\mu g\ m^{-3}$)	NO_2 ($\mu g\ m^{-3}$)	NO_2 ($\mu g\ m^{-3}$)	NO_2 ($\mu g\ m^{-3}$)	NO_2 ($\mu g\ m^{-3}$)
2	318	437	287	318	508	412
3	278	411	284	244	504	392
4	325	344	238	271	427	361
5	271	341	210	236	405	399
6	236	297	178	234	368	298
7	204	364	205	197	375	302
8	251	355	262	240	412	331
9	280	428	323	264	452	449
10	298	420	297	280	501	389
11	232	398	287	214	500	332
12	361	380	282	360	427	353

None of these studies however, have investigated indoor air quality in the context of temperature gradients, within UK railway depots in which the trains are often held in enclosed buildings, with poorer rates of ventilation as compared to that available in a station. This PhD project will use the information from previous authors to compare against the planned, ambient concentration measurements planned for the four railway depots of Northern Rail. The previous literature on train station air quality measurements will be used as a reference for the indoor air quality measurements at the Manchester Victoria station considered in this project.

2.7.6 Automatic and non-automatic monitoring sites

A number of councils and regions have conducted automatic monitoring and non-automatic monitoring for monitoring roadside air pollution. Automatic monitoring sites record temporal data of air pollutants, such as NO_2, or PM_{10}, using specialist equipment such as a TEOM with MCERTS (Monitoring Certification Scheme) certification for monitoring PM, as $PM_{2.5}$ and PM_{10}, and a chemilumescence analyser for NO_2. Typically these, are positioned in the same location, as an AURN. A non-automatic monitoring site, record spatial data of air pollutants, typically, used for NO_2, in which diffusion tubes are using to determine a single monthly average

concentration of NO_2 at a fixed location. As a low-cost technology, as is the case for diffusion tubes, it allows deployment on a large scale, in multiple locations with very easy installation and maintenance, in contrast to the automatic monitoring sites, which contain very expensive, high specification equipment and need sufficient training and expertise in order to install, maintain and operate.

For this project, with a major focus on the Leeds railway depot of Neville Hill, there are 11 continuous monitoring stations for NO_x across the Leeds city region, 2 of these are operated by the AURN network and 9 by Leeds City Council (LCC), as indicated in Figure 2.21. Details of the 9 LCC locations are provided in Table 2.24.

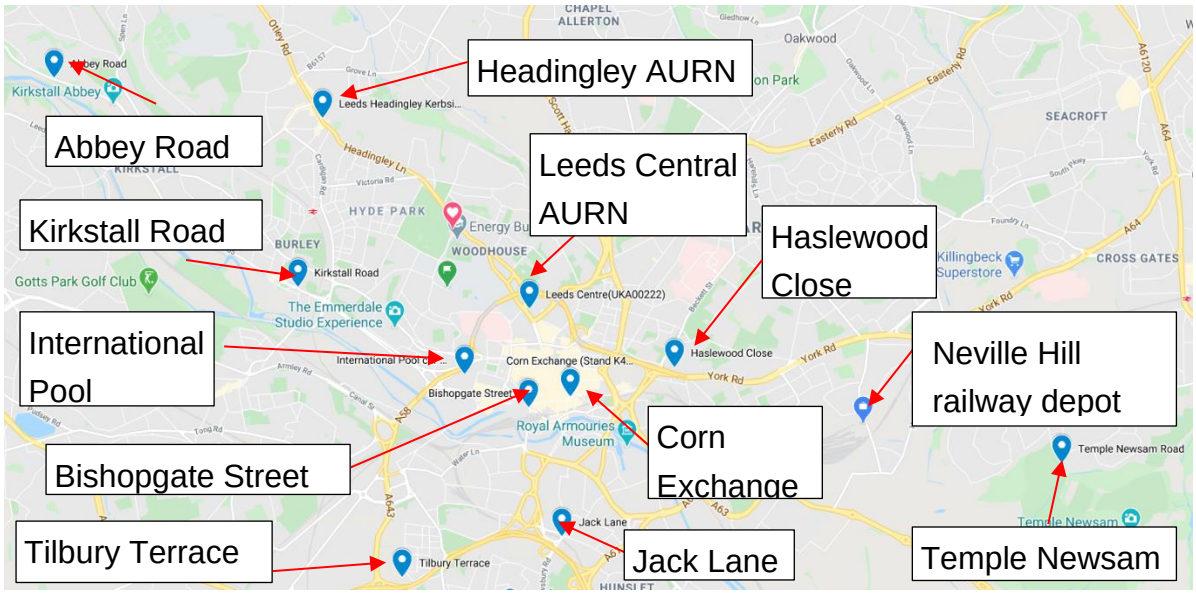


Figure 2.21 Automatic monitoring sites for NO_x in LCC (Google, 2022b)

Table 2.24 Daily and hourly averaged NO_2 data from 9 automatic monitoring sites maintained by Leeds City Council in the Leeds city region (LCC, 2019c)

Site ID	Site Name	Site type	X OS Grid Ref	Y OS Grid ref	Distance to kerbside (m^2)	Inlet Height (m)	Hourly NO_2 (µg m^{-3}) 2015-18	Daily NO_2 (µg m^{-3}) 2015-18
A2	Corn Exchange	Kerbside	430358	433422	1	2.7	53	18
A6	Haslewood Close	Roadside	431268	433701	7	3.3	42	37
A9	Jack Lane, Hunslet	Roadside	430731	431911	5	2.7	43	26
A17	Kirkstall Rd	Roadside	427147	434789	5	2.7	28	26
A18	Temple Newsam	Other	435940	432271	n/a	2.4	19	17
A19	Tilbury Terrace	Roadside	428830	431657	15	1.5	35	34
A20	International Pool	Roadside	429329	433672	4	1.5	41	43
A21	Bishopgate Street	Roadside	429932	433370	3	1.5	64	50
A22	Abbey Road	Roadside	426286	435784	2	1.5	41	15

The nearest NO_x automatic monitoring site to the Neville Hill railway depot is the Temple Newsam Road site. In relation to the typical roadside data in the Leeds city region, LCC have a chemiluminescence analyser in the Temple Newsam area which is 1.9 miles east of the Neville Hill railway depot (DEFRA, 2017b). At Temple Newsam site, the annual roadside NO_2 was measured at 16 µg m^{-3} in 2018 with the monthly values varying between 12 and 20 µg m^{-3} as seen in Table 2.25 (LCC, 2019c).

Table 2.25 Monthly NO_2 concentrations at Temple Newsam in 2018 obtained from LCC (LCC, 2019c)

Month	**Monthly NO_2 (µg m^{-3})**
Jan	20
Feb	19
Mar	17
Apr	15
May	14
Jun	12
Jul	12
Aug	14
Sep	15
Oct	17
Nov	17
Dec	20
Annual average	**16**

For each of the 4 railway depots and 1 train station, in this study, there are also non-automatic monitoring sites in relative close proximity to each of these locations. Allerton railway depot has a nearby non-automatic monitoring site on Speke Rd (Site ID: S11, XY: 340946, 384256) as shown in Figure 2.22 which is a 0.8 mi walk, South of the Allerton railway depot (LICC, 2020a). Heaton railway depot has a nearby non-automatic monitoring site on Coast Rd (Site ID: DT84, XY: 428143, 566886) as shown in Figure 2.23 which is 0.7 mi by car North of Heaton railway depot (NCC, 2019b). Neville Hill railway depot has a nearby non-automatic monitoring site on

Osmondthorpe Ln (Site ID: D383, XY: 433132, 434034) as shown in Figure 2.24 which is 0.6 mi walk, North of the Neville Hill railway depot (LCC, 2019b). Newton Heath railway depot has a nearby non-automatic monitoring site on Mellor St (Site ID: OLMSNO, XY: 388871, 400997) as shown in Figure 2.25 which is a 0.8 mi walk, East of the Newton Heath railway depot (GMCA, 2019a). Manchester Victoria station has a nearby non-automatic monitoring site by the National Football Museum (Site ID: MA26ANO, XY: 383971, 398876) as shown in Figure 2.26 which is a 276 ft walk, West of the Manchester Victoria station (GMCA, 2019b).

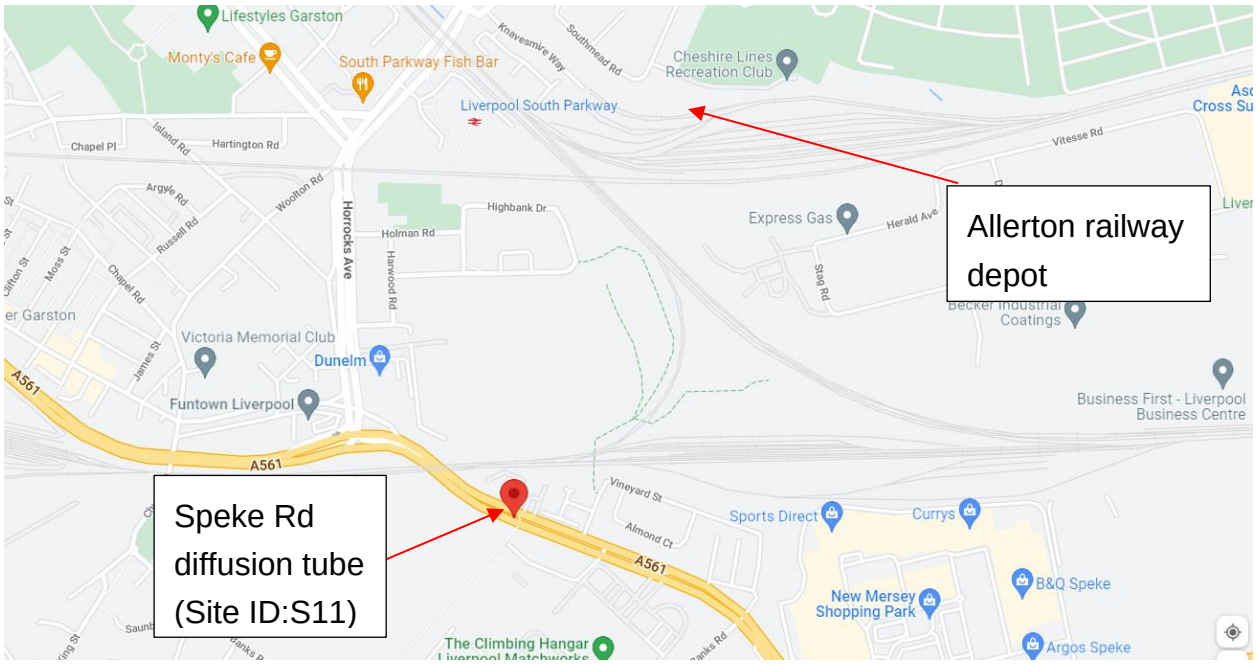


Figure 2.22 Nearest Liverpool City Council (LICC) non-automatic monitoring site in relation to the Allerton railway depot (Google, 2022g; LICC, 2020b)

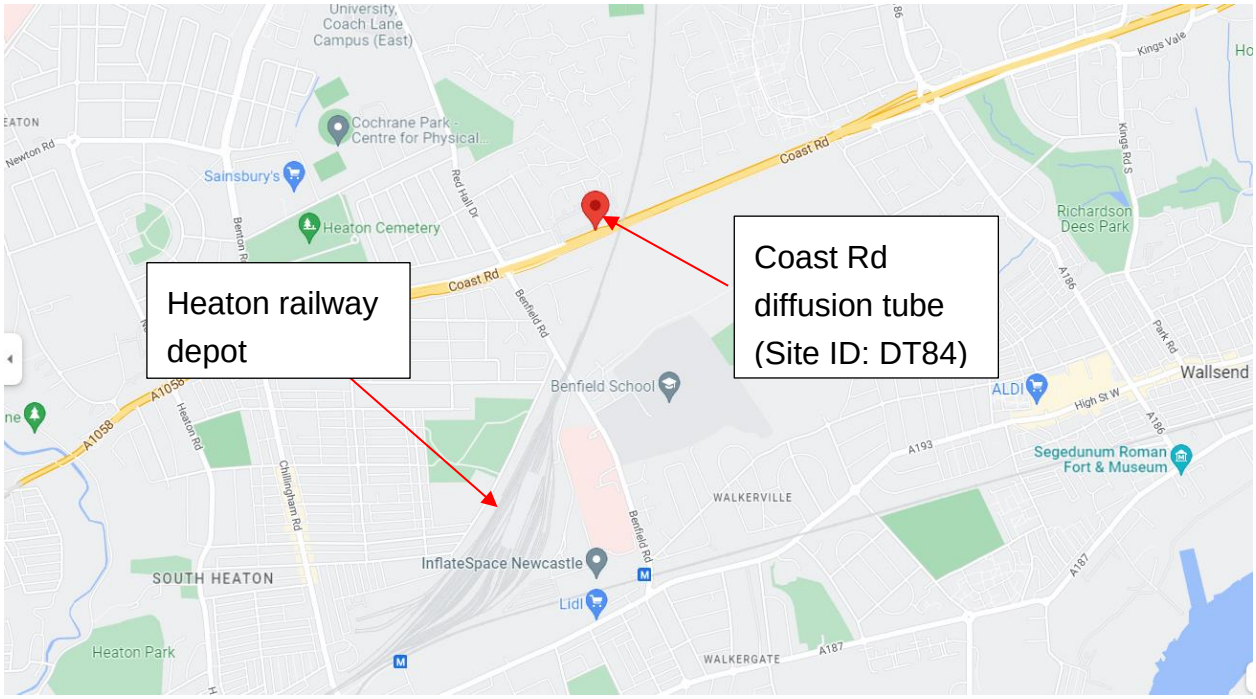


Figure 2.23 Nearest Newcastle City Council (NCC) non-automatic monitoring site in relation to the Heaton railway depot (Google, 2022c; NCC, 2019a)

Figure 2.24 Nearest Leeds City Council non-automatic monitoring site in relation to the Neville Hill railway depot (Google, 2022d; LCC, 2019a)

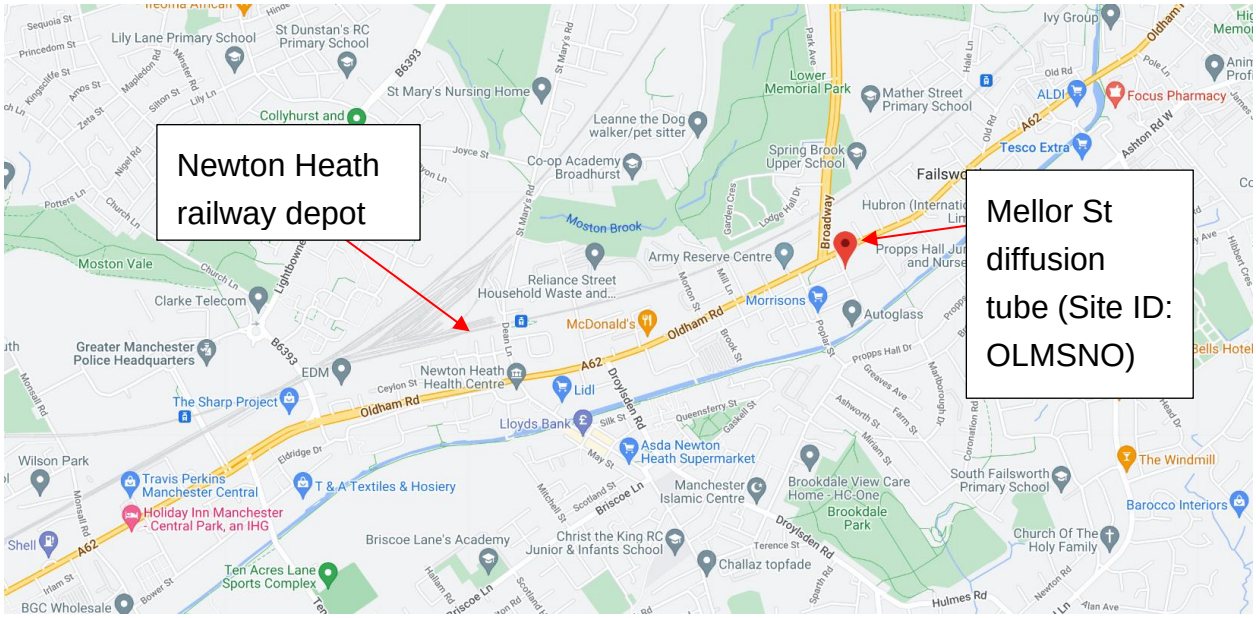


Figure 2.25 Nearest Greater Manchester Combined Authority (GMCA) non-automatic monitoring site in relation to the Newton Heath railway depot (Google, 2022f; GMCA, 2019b)

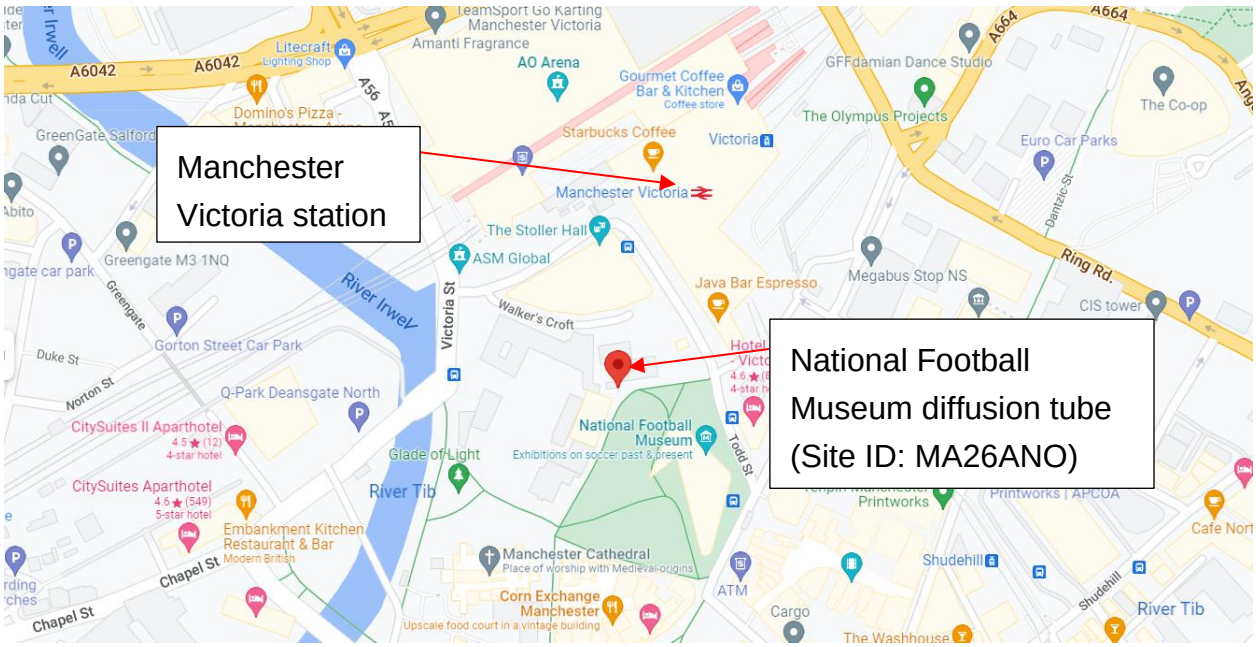


Figure 2.26 Nearest Greater Manchester non-automatic monitoring site in relation to the Manchester Victoria station (Google, 2022e; GMCA, 2019a)

2.8 Indoor temperature gradients

An indoor temperature gradient, is the term used to describe temperature changes with height in indoor environments, a positive temperature gradient

indicates an increase in indoor temperature with height. This is of particular interest to this project, as the phenomena of stagnant volumes of diesel exhaust occurring during heavy maintenance tests at Northern's Rail railway depots has led to the theory that a positive temperature gradient may be occurring within the depot. A positive temperature gradient arises due to poor buoyancy because colder air sits below warmer air, limiting the vertical mixing air and pollutants.

There are studies in literature on indoor temperature gradients, although outside of the rail sector, which are of relevance to this study. Boon and Battams (Boon and Battams, 1988) observed temperature gradient behaviour within an indoor, livestock environment with ground-level heaters. The study observed a change in the indoor, vertical temperature profile following the introduction of mechanical ventilation facilitated air mixing (Boon and Battams, 1988). This is interesting to note, as it highlights a positive temperature gradient leading to poor air mixing, which is a scenario that could replicate in the similarly poorly mixed, indoor environment considered in this study. As well as temperature gradients, concentration gradients can also occur, in which the concentration of a given pollutant, can increase in height. MacCarty et al. (MacCarty et al., 2020) examined both temperature and pollutant concentration gradients, when evaluating $PM_{2.5}$ in a test kitchen, modelled on a Nepalese rural, cookstove environment. The study showed a change in the indoor, vertical concentration of $PM_{2.5}$ of almost 30000 µg m^{-3}, with $PM_{2.5}$ concentrations rising from 833 µg m^{-3} at 0.6 m to 29583 µg m^{-3} at 2.4 m, with a ventilation rate of 15 ACH (air changes per hour). A vertical, temperature profile of approximately 5 °C between heights of 0.6 m and 2.2 m, was observed, indicating a positive temperature gradient (MacCarty et al., 2020). Building on previous work in literature, this study will assessing whether similar increases in indoor NO_2 concentration and temperature are observed with changing height within a railway depot environment. There is very little research data in the rail sector for indoor temperature gradients, in particular within indoor, maintenance rail environments. This is clearly a gap identified in the literature field and the work in this project will aid this.

2.9 Ventilation rate

This project, will investigate the ventilation rate of a number of fans in the Neville Hill railway depot and whether the existing roof ventilation fans are sufficient to extract the train exhaust fumes from the railway depot.

2.9.1 Indoor building regulations for ventilation rate

In the UK, the Chartered Institute of Building Services Engineers (CIBSE) mandate a minimum ventilation rate of 10 l s^{-1} per person for office applications (CIBSE, 2016a). The HSE guidance note EH22 specifies a minimum of 3 ACH (air changes per hour) with a recommendation of 8 ACH. The air changes per hour rating according to CIBSE “is falling out of favour because of its high dependency on room volume, which fails to reflect the physical need to provide fresh air or remove heat” (CIBSE, 2016b). There is no ACH specifically for transportation buildings such as railway depots which is confirmed by the CIBSE Guide B recommendations. Typically the ACH value for a car park is used as a de facto measure for railway depots with ACH of 6 as advised by Network Rail. The ACH for car parks is given in the 2005 document: "CIBSE Guide B - Heating, Ventilating, Air Conditioning and Refrigeration - 2. Ventilation and air conditioning" (CIBSE, 2005; Butcher).The 6 ACH for car parks is also referred to in the: "HM Government - Building Regulations 2010 - F1 Means of ventilation" (Government, 2010). This 6 ACH for car parks is also referred to in the: "HM Government - Building Regulations 2010 - F1 Means of ventilation" (Government, 2010).

2.10 Gaps in the Research

From reviewing the literature there appears to be limited studies of pollutant concentration gradients within indoor industrial environments with none conducted thus far within the rail sector. This feeds into research question 1, in which the factors affecting the air quality within UK railway depots are investigated. In terms of ambient air quality monitoring there are a number of studies both in the academic and the commercial sector, regarding ambient pollutant concentration monitoring. The RSSB have also performed emissions tests on a number of engines now utilised by Northern Rail in their DMU fleet, however these tests although useful did not investigate the individual power settings of the train, of which there are 8 power settings (Ian, 2006b) under typical railway depot conditions i.e. within a confined environment with the engine revved up whilst the train is static. This work will hope to add information on the emission rating during the typical maintenance schedule of Northern Rail’s DMUs and this is detailed in research question 2. Regarding aftertreatment technologies, the RSSB have in the past, conducted CRT tests on two Cummins engines utilised in the rail sector, in which one of these, the Cummins NTA855R3 is utilised by Northern Rail (Ian, 2006a). The tests showed great promise with reductions in a number of engine pollutants, including CO, NO_2 and THC.

However, the tests did not cover SCR retrofitted trains, which is designed to reduce the amount of NO and NO_2 in the engine. This links with research question 3 in exploring the effect of aftertreatment technologies on Northern Rail's trains. In the area of alternative fuels, tests have been conducted by Deutsche Bahn in Germany using GTL within a MTU engine.(UIC, 2007). However, other alternative fuels, such as HVO have not been tested within rail. A gap has been identified to assess the suitability of alternative fuels such as GTL and HVO as rail replacement fuels for the currently used red diesel within the UK market. This links to research question 4.

Chapter 3 Methodology

3.1 Overview

In this chapter, experiments are outlined to assess the rail vehicle exhaust emissions in a railway depot, the indoor air quality within both railway depots and a train station, railway depot ventilation effectiveness and the WTW (Well to Wheel) contributions of individual air pollutants and CO_2 for diesel rail engine fuels. The purpose of these experiments are to address the 4 research questions of this study, and to put forward recommendations to improve the air quality and reduce the carbon footprint, for 5 rail locations (4 railway depots and 1 train station).

This work will align with wider work by the RSSB (Rail Safety & Standards Boards) in rail air quality research and support the rail air quality improvement ambitions of the UK Clean Air Strategy 2019 (RSSB, 2020; DEFRA, 2019).

The experiments of this chapter are divided into two types, field experiments set-out in sections 3.4 & 3.6-3.8, and desk-based modelling set-out in sections 3.5 & 3.9, including the use of a box model (section 3.5) and WTW analysis (section 3.9). The field experiments cover 5 different Northern Rail locations, of which 4 are railway depots and 1 is a train station. These 4 railway depots are Allerton railway depot of Liverpool, Newton Heath railway depot of Manchester, Neville Hill railway depot of Leeds and Heaton railway depot of Newcastle with further details about each of the depots in section 3.2. The single train station of this project is Manchester Victoria of Manchester, with further details about this station in section 3.2. Specifications of the DMU (diesel multiple unit) trains present within the 4 railway depots are listed in section 3.3 including information such as engine type.

Within each of the locations, diffusion tube measurements are utilised to assess the spatial variations in NO_2 (nitrogen dioxide), within the main zones of activity, as outlined in sections 3.6-3.8. In the depots, this corresponds to the maintenance sheds with a high quantity of repair work. In the Allerton, Newton Heaton and Heaton railway depots, the shed with the highest amount of repair work activity is known as the main shed. In the railway depot of Neville Hill, there are two sheds of repair work activity, a repair shed and a service shed. In the Manchester Victoria train station, the diffusion tubes cover locations across each of the platforms and selected locations across the station, including outside of the shop area. Neville Hill, a railway depot of particular of concern for Northern Rail for air quality, is utilised as the major focus for investigation of indoor air quality, with the section of the repair

shed, the largest zone of maintenance activity, having reported smoke plumes above the trains but below the shed ceiling level.

3.1.1 Key terminology

For each of the railway depots, each internal railway line is referred to as a ‘road’. These roads are numbered in integers starting from 1. There is however different nomenclature between the railway depots, with Allerton and Newton Heath depot using the system of road followed by a number, e.g. Road 1. However, for Neville Hill and Heaton, a different system is used in which the number precedes the word ‘road’, i.e. 1 Road.

3.1.2 Allerton depot, Liverpool

Allerton railway depot (XY: 341070, 384969) pictured in Figure 3.1 located in Liverpool nearby to the Liverpool South Parkway station. It consists of 2 sheds, a main shed and a wheel lathe shed. The main shed (92 x 38 x 7 m) shown in Figure 3.2 is divided into two sections, with 2 rail lines (Road 4 and 5) for electric trains and 3 rail lines for diesel trains (Roads 1, 2 & 3).

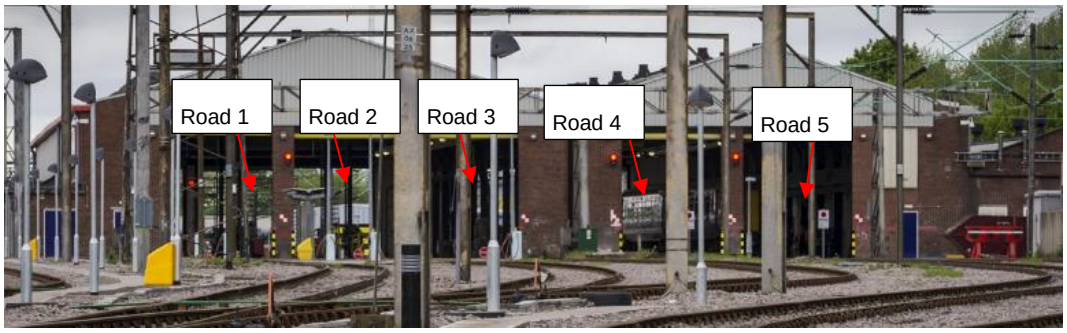


Figure 3.1 Main Shed of Allerton Railway depot, Liverpool, (Roads 1-5) (RTM, 2016)

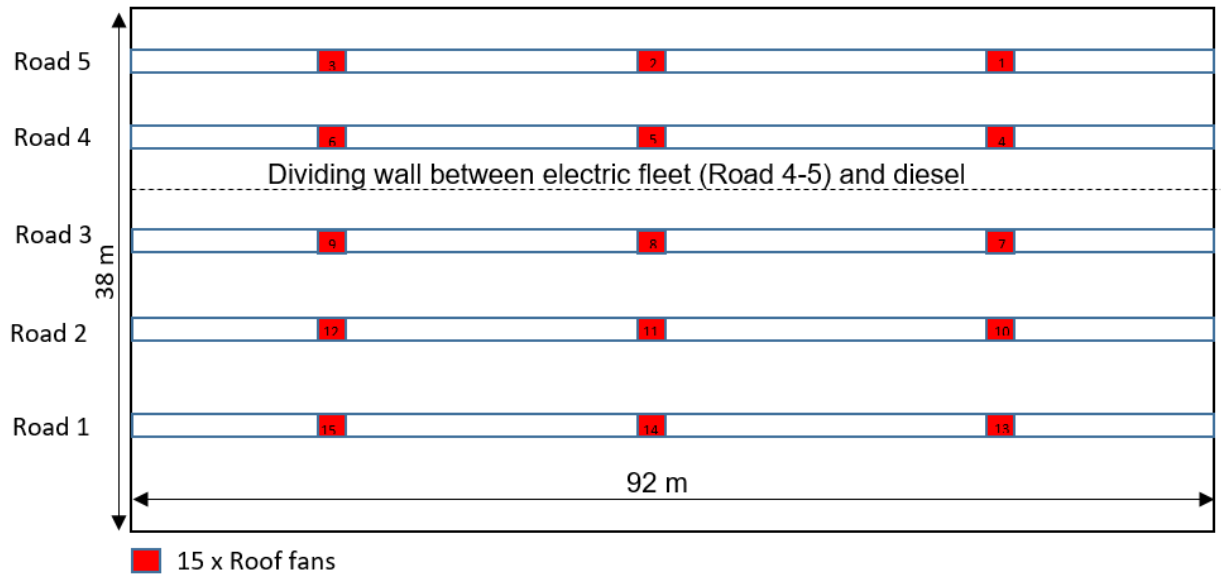


Figure 3.2 Main shed layout of Allerton railway depot (Northern)

The depot is responsible for approximately 26 diesel trains (Class 142, 150 and 156) and 24 electric trains (Class 319). There are 15 roof ventilation fans within the main shed, and these operate on an on/off basis. There is no fan speed control available. There is no air quality monitoring systems in place within the main shed at Allerton.

3.1.3 Heaton depot, Newcastle

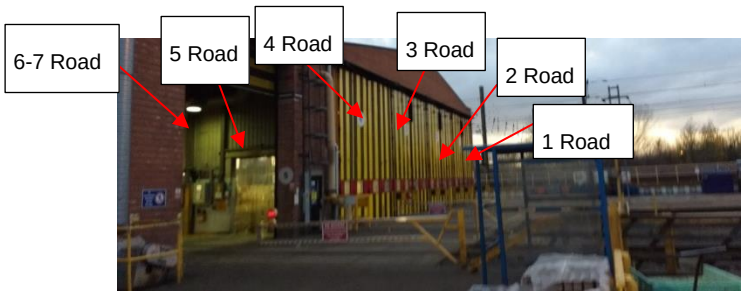


Figure 3.3 Main Shed of Heaton railway depot, Newcastle (Roads 1-7)

Heaton railway depot (XY: 341070, 384969) pictured in Figure 3.3 is located in Newcastle and is about 2 miles from Newcastle train station. It consists of 1 main shed (270 x 44 x 8.9 m) consisting of 7 rail lines (1-7 Road), as shown in detail in Figure 3.5. 1-5 Roads are thoroughfare and 6-7 Road are sealed at one end. 6 and 7 Road are used by another train operator for the Grand Central trains. There are 73 roof ventilation fans, highlighted in red and green boxes, in Figure 3.5. In addition, there are 9 local extraction ventilation (LEV) systems within the main shed, in which 5 LEVs are on 5 road, 2 LEVs on 6 road and 2 LEVs on 7 road. There is no variable

speed control of the fans. There is also 8 hanging real-time CO monitors, with half of these on road 5 and the other half on road 5, with an example of one of the CO monitors shown in Figure 3.4.

Figure 3.4 Ceiling level CO monitor in the Heaton railway depot

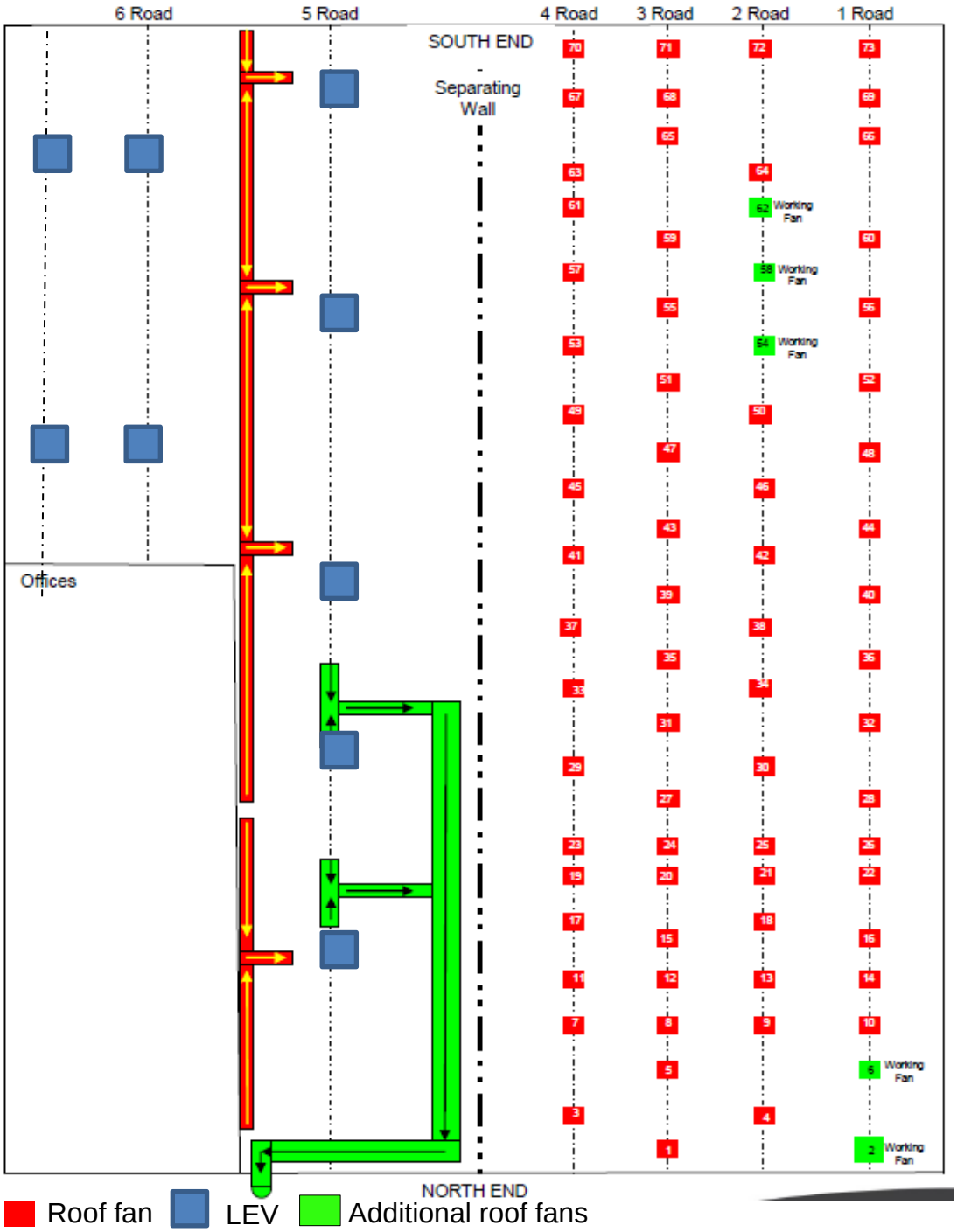


Figure 3.5 Main shed layout of Heaton railway depot (reproduced from ESG report) (ESG, 2016a)

3.1.4 Neville Hill railway depot, Leeds

Neville Hill railway depot pictured in Figure 3.6 is located in Leeds and is approximately 3 miles east of Leeds train station. It consists of 2 sheds, a repair shed (100 x 36 x 7.5 m), shown in Figure 3.7 for heavy maintenance work and a

service shed (200 x 10.4 x 7.3 m) for lighter maintenance, which is pictured in Figure 3.8.

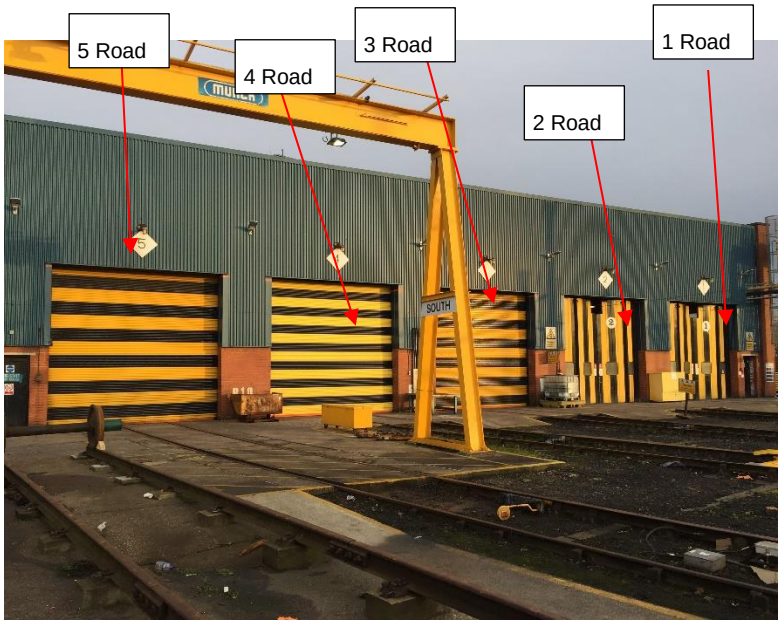


Figure 3.6 Main Shed of Neville Hill Railway depot, Leeds, (Roads 1-5)

The repair shed has 5 roads and the service shed has 4 roads. In the repair shed, 1 Road is designated for the electric trains, 2 Road and 5 Road are used for both electric and diesel trains with 3 Road and 4 Road solely used for diesel trains. The repair shed is sealed at the eastern entrance, allowing trains to enter and leave via a single series of doors at the western entrance. The service shed is shared with the train operator East Midlands Railway who utilise Roads 1 and 2 of the service shed, with Northern utilising Roads 3 and 4. There are 28 roof fans in the repair shed as seen in Figure 3.7 and 21 roof fans in Northern's service shed section as shown in Figure 3.8. There is no variable speed control of the fans. The fans work on an on/off basis and are switched on in line zones of approximately 2 fans in each.

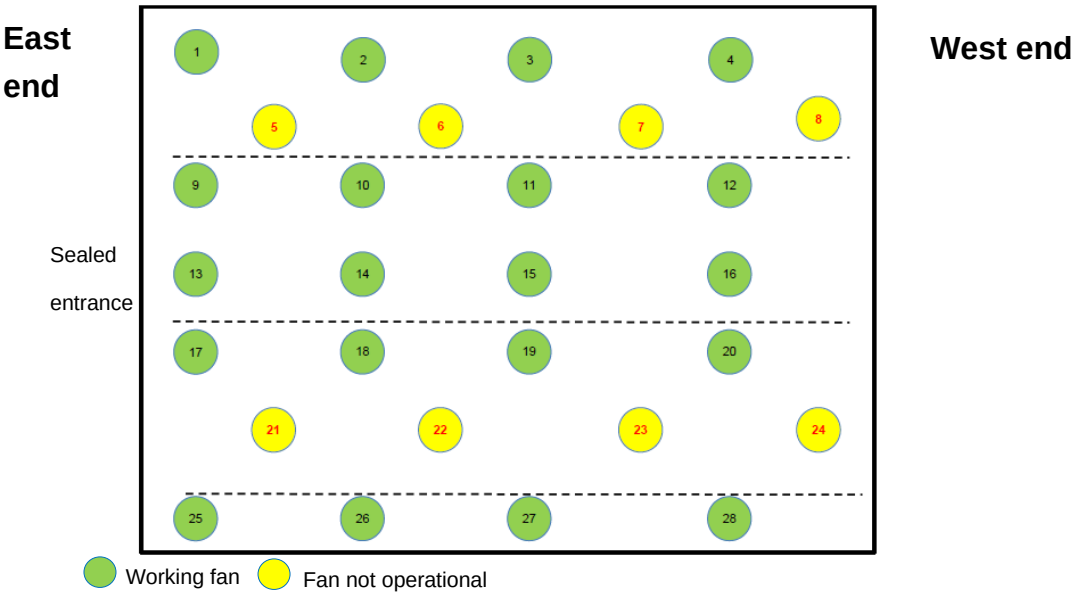


Figure 3.7 Repair shed layout of Neville Hill railway depot (reproduced from ESG) (ESG, 2015)

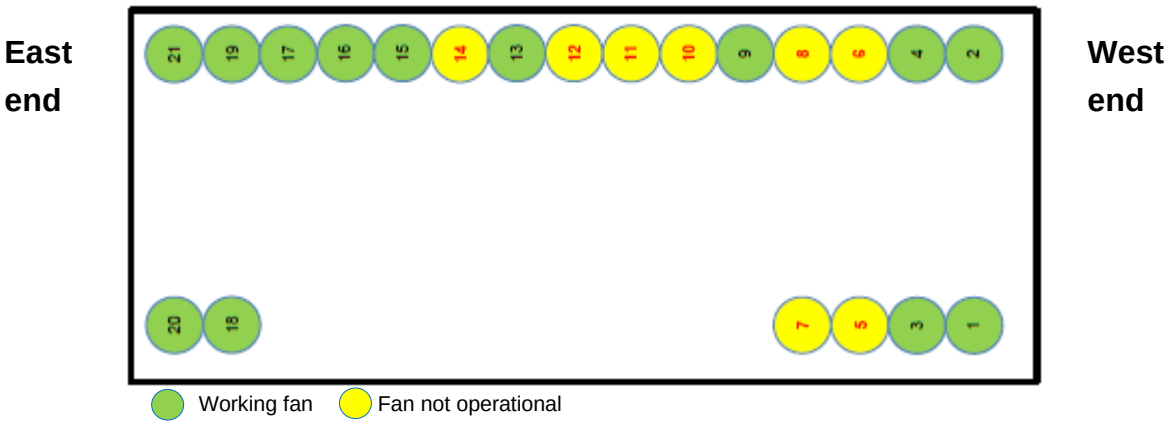


Figure 3.8 Service Shed layout of Neville Hill railway depot (reproduced from ESG) (ESG, 2015)

3.1.5 Newton Heath depot, Manchester

Figure 3.9 Main Shed of Newton Heath railway depot, Manchester (Roads 4-7)

The Newton Heath railway depot pictured in Figure 3.9 is located in the east of Manchester, and is about 3 miles north-east of Manchester Victoria train station. It consists of four sheds, a paint shed (Roads 1-3), a main shed (Roads 4-7), a parlour shed (Roads 8-10), and a wash and carriage shed. The trains are not switched on in the paint shed and the wash shed. The main shed (135.6 x 27.6 x 10.7 m) and parlour shed (50.8 x 21.6 x 8.7 m) form part of one building, as seen in Figure 3.10 and are thoroughfare with trains entering and exiting via different entrances. There are 5 fans in the main shed and 9 fans in the parlour shed, as indicated by the green square boxes of Figure 3.10. These fans can be individual switched on, and do have variable speed control, with metered flow rates. In addition to the roof fans, there is one LEV system located on Road 4.

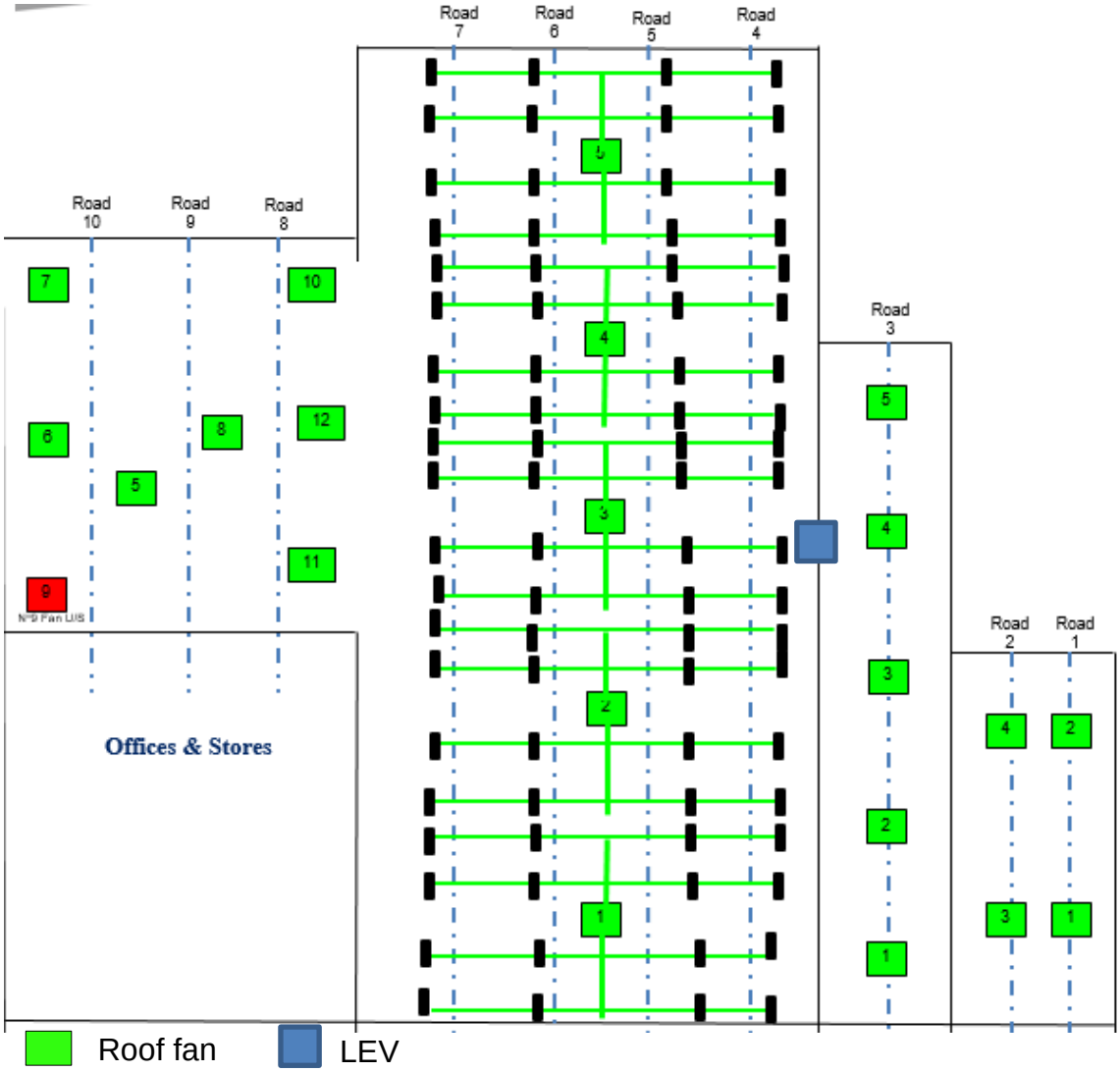


Figure 3.10 Main shed layout of Newton Heath Railway depot layout (reproduced from ESG) (ESG, 2016b)

3.1.6 Train start-up procedure

There are two types of maintenance carried out at the depots, light maintenance work known as A exams and heavy maintenace works known as B exams. Typically the differenece between the two exams, is that the A exams do not require the engine to be started, and the maintenance work is conducted using power from the electric powerbanks known as ‘shore supplies’ in the rail sector. Light maintenance work may include checking the compressed air on the train, and making sure the lighting is working on the trains. For the B exams, the trains are powered on, using the engine fuel, and are run mostly on the ‘idle setting’, however for some B exams such as the ‘run-ups’, the train is required to cycle through all the

notch settings up till maximum notch 7 and then cycled back down to idle, i.e. notch 0. There are 8 different power settings which are tested, with each of these setttings referred to as notches. In order to change between the notches a single gear shift is moved from the initial position of upright, downwards for increasing notch settings. Some typical procedures for the B exams are included in the Appendix B.

When under heavy maintenace work, the intention is to test whether or not the train are fit for passenger service. The driver control panel for the DMU is shown in Figure 3.11 , with the different powers associated with the term, ‘notches’. The initial position of notch 0, indicates the idle position. The gear stick is moved from notch 1 to higher level notches for increasing power. Notch 7 indicates maximum power. The standard procedure for the heavy maintenance known as ‘run-ups’ involve the drivers, shifting through the notch settings under stationary train conditions. Initially, the engine is started via a key and the driver moves the gear stick from an initial position of notch 0, corresponding to idle power and held there for about 8 mins. Following this the engine power is increasing by moving the gear stick from notch 0 to the notch 7 through every notch position and holding at each notch approximately 15 s; of which notch 7 corresponds to high speed idle. The driver then decreases engine power by moving the gear stick from notch 7 down through each of the notch settings until notch 0. At the higher notch settings, visible quantities of white smoke are released from the exhaust. Typical power values for each of the notch power settings are shown in Table 3.1 with load, which were obtained from independent dynamometer tests conducted by the contractor, LH for a selection of Cummins engines (LH, 2018). This means that that the power values with load can’t be used directly for comparison with the exhaust emission test data from this study. Percentage of maximum power values for all four engines are given in Table 3.2. It must be noted that in this study, the run-ups test for exhaust emission monitoring is conducted without load. Higher notch settings potentially can lead to greater emission rates from the exhaust, due to the greater amount of fuel consumed at these high power settings.

Figure 3.11 Vehicle control panel for the DMU

Table 3.1 Power values for individual notches observed during dyno testing for Cummins engines (LH, 2018)

			Notch							
Engine	**Train**	**Units**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Cummins LTA-10R	142	HP	5	15.7	38.3	92	125	152	184	214
Cummins NTA855R1	158	HP	7	30	60	140	195	240	285	333
Cummins NTA855R3	158	HP	5	30	50	140	205	260	315	381
Cummins NTA855R5	15X	HP	5	25	30	100	165	200	225	270

The power values are quoted in Horsepower (HP) with an accuracy of ± 5 HP, 15X denotes the following trains classes: 150,153,155, 156 and 158.

Table 3.2 Percentage power values from the total power values for individual notches observed during dyno testing for Cummins engines (LH, 2018)

			Notch							
Engine	**Train**	**Units**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Cummins LTA-10R	142	%	2	7	18	43	58	71	86	100
Cummins NTA855R1	158	%	2	9	18	42	59	72	86	100
Cummins NTA855R3	158	%	1	8	13	37	54	68	83	100
Cummins NTA855R5	15X	%	2	9	11	37	61	74	83	100

3.2 Manchester Victoria station, Manchester

Manchester Victoria is a train station located in the centre of Manchester which was constructed in 1844. The station provides both train services and tram services. Two train operating companies provide train services from the station, Transpenine Express (TPE) and Northern Rail. TPE provides intercity services between Manchester, Newcastle, Middlesbrough and Liverpool. Northern Rail provides a mixture of intercity services such as that to Leeds, in addition to providing shorter commuter routes to areas in Greater Manchester such as Stalybridge. The tram service is operated by Transport for Greater Manchester (TfGM) under the service name of Metrolink, acting as an intermediary station for journeys to towns within the Greater Manchester area including the terminus point of Altrincham, Eccles, Bury, Rochdale and Ashton-Under-Lyne. Manchester Victoria consists of 6 rail platforms

and 4 tram platforms shown in Figure 3.12. Two of the rail platforms (1 & 2) are under a high roof of height 20 m, with the remaining 4 of the platforms (3-6), underneath the Manchester Arena entertainment complex.

There are a series of approximately 50 rectangular, roof extraction fans along platforms 3-6 of dimension 1 m by 2 m positioned just above the platform spaced approximately 5 m from each other, at a height of 4 m above ground level. The fans are connected to a series of 10 air flow extraction ducts which are vented outside of the station above the western end of the platform 3. The lengths of platforms 3, 4, 5 and 6 are approximately 200 m for each platform when measuring the distance between the corresponding rail signal lights at the Western and Eastern ends of the platform. Platforms 3-6 are interconnected via a passenger bridge (41 x 8.9 x 2.8 m) at 5.2 m above ground level, with stairways to enter and exit each of the four platforms. The ventilation system along the platforms is controlled by the Manchester Arena, who have a contractor, SMG Europe to oversee the system on their behalf, see Appendix C for further details. The ventilation system has pollutant sensors for NO_2, CO and CO_2 which activate the platform fans once the ambient pollutants exceed two pre-set alarm levels, with alarm level one set at 10 ppm CO, 0.5 ppm NO_2, 700 ppm CO_2, and alarm level two at 20 ppm CO, 2.5 ppm NO_2 and 1050 ppm CO_2; further details are available in Appendix D (Gee, 2019). Trains are parked typically near or underneath the passenger bridge, for passenger embarking for onward journeys. This can have the adverse effect of injecting engine exhaust pollutants into the above passenger bridge between platforms 3-6, which has no ventilation system in the bridge area, as of March 2020.

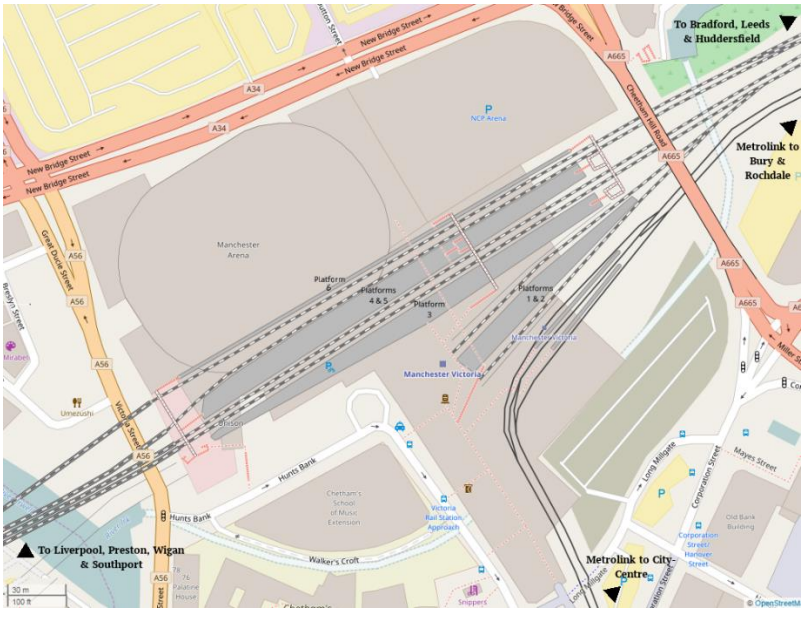


Figure 3.12 Manchester Victoria station layout (Rail, 2022)

3.3 Specification of the DMUs

3.3.1 Angel Railways leased trains

Table 3.3 Angel Railways leased trains (Angel, 2017a; Angel, 2017b; Angel, 2017c; Angel, 2017d; Angel, 2017e)

Class	142	150	153	156	158
Manufacturer	BREL/Leyland Pacer	BREL Sprinter	Leyland Bus Super Sprinter	Metro-Cammell Super Sprinter	BREL Express Sprinter
Year of Build	1985 -87	1985-87	1987 - 88	1987-89	1989 - 92
Length	15.55 m	19.74 m	23.21 m	23.03m	22.57 m
Width	2.80 m	2.82 m	2.70 m	2.73m	2.70 m
Weight	24.5 T	38.1 T (DMS), 38.3 T (DMSL) (150/1); 36.5 T (DMS), 37.5 T (DMS) (150/2)	41.2 T	36.1 T (DMS), 38.6 T (DMSL)	38.5 T
Transmission	Voith T211r hydraulic and SCG RF420i final drive	Voith T211r hydraulic and Gmeinder GM180 final drive	Voith T211r hydraulic and Gmeinder GM190 final drive	Voith T211r hydraulic and Gmeinder GM190 final drive	Voith T211rz or T211rzz hydraulic and Gmeinder GM 190 final drive.

Class	142	150	153	156	158
Engines	Cummins LTA 10-R, 225 HP at 1950 rpm	Cummins NT855R5, 285 HP at 2100 rpm	Cummins NT855R5, 285 HP at 2100 rpm	Cummins NT855R5, 285 HP at 2100 rpm	Cummins NTA855R1, 350 HP at 2100 rpm or Cummins NTA855R3, 400 HP at 1900 rpm, or Perkins 2006-TWH 350 HP at 2100 rpm
Maximum Speed	75 mph	75 mph	75 mph	75 mph	90 mph
Traction Type	DMU	DMU	DMU	DMU	DMU
Interoperability	Other Sprinters, Pacers and Turbostars	Other Sprinters, Pacers and Turbostars	Other Sprinters, Pacers, 170 & 172	Other Sprinters, Pacers and Turbostars	Other Sprinters, Pacers and Turbostars
Formation	Operate as 2-car units with toilet in one vehicle	Operate as 2-car units with toilet in one vehicle or 3-car unit with class 150/2 coupled between class 150/1 vehicles	Operate as 1-car unit	Operate as 2-car units with toilet in one vehicle.	Operate as 2-car units with toilet in both vehicles

3.3.2 Porterbrook leased trains

Table 3.4 Porterbrook leased trains (Porterbrook, 2017a; Porterbrook, 2017b; Porterbrook, 2017c; Porterbrook, 2017d; Porterbrook, 2017e; Porterbrook, 2017f; Porterbrook, 2017g)

Class	144	150	153	155	156	158	170
Year of Build	1986-1987	1986-1987	1987-1988	1988	1987-1989	1989-1992	1998-2002
Engines	Cummins LTA 10-R of 172kW (230hp) @ 2100 rpm	Cummins NT855R5 of 213kW (285hp) @ 2100 rpm	Cummins NT855R5 of 213kW (285hp) @ 2100 rpm	Cummins NT855R5 of 213kW (285hp) @ 2100 rpm	Cummins NT855R5 of 213kW (285hp) @2100 rpm	Cummins NTA855R(1) of 260kW (350hp) @1900 rpm	MTU 6R183TD13H of 315kW (422 HP) @ 1900 rpm
Maximum Speed	75 mph	75 mph	75 mph	75 mph	75 mph	90 mph	100 mph

3.4 Rail exhaust emission measurement

In this experiment, exhaust emission measurements are outlined for a number of single DMUs under stationary conditions to support research question 1: ‘What are the emission levels of Northern Rail DMUs in a railway depot, and how do these emissions compare to other vehicles?’

For the exhaust emission tests the DMU engines were operating without load applied, and the trains involved in the testing are listed in Table 3.5. The trains were located in repair shed of Neville Hill. The tests were conducted by the contractor, Horiba UK using a Horiba OBS-One gas analyser and PN unit. The University of Leeds performed the data analysis. It was planned to test the trains, at 1 min for each of the 8 notch settings on the gear shift, from idle (notch 0), to maximum power (notch 7) and then from maximum power to notch 0. Tests were designed for 1 min for the notch settings 1-7 with extra time allowed for the idle setting, due to the start-up procedure from Northern personnel. The test procedure is fully detailed in Table 3.8. The species monitored are CO, CO_2, NO, NO_2, NO_x, THC and PN (Particle Number). A discussion of Horiba PEMS exhaust emission data will be covered in Chapter 4 with comparisons against literature data.

Table 3.5 Trains selected for the emission test in the repair shed

Train	**Engine**
144010	Cummins LTA-10R
150142	Cummins NTA855R5
153378	Cummins NTA855R5
158849	Perkins 2006-TWH
158903	Cummins NTA855R1

3.4.1 Set-up of PEMS system with a single DMU carriage

The Horiba OBS-ONE PEMS was connected to the exhaust pipe of a single DMU section of 1 train carriage, chosen from Table 3.5. It consists of two sub-units, a PN unit and a gaseous unit. The gaseous unit itself consists of three sub-units, a FID (flame ionisation detector) for measuring total hydrocarbons, a NDIR (non-dispersive infrared) for measuring CO and CO_2 and a CLD (chemiluminescence

detector) for measuring NO, NO_2 and NO_x. This is done, by using two sample lines (one for PN and one for the gaseous analyser), connected to a pitot tube, as shown in Figure 3.13. The Pitot tube is attached to a curved pipe attachment to allow for the difference in diameter between the exhaust pipe and the Pitot tube. The other end of the pipe attachment is fitted to the exhaust pipe, located at the end of the DMU unit. The exhaust pipe is positioned vertically with a 0.2 m protrusion above the top of the train.

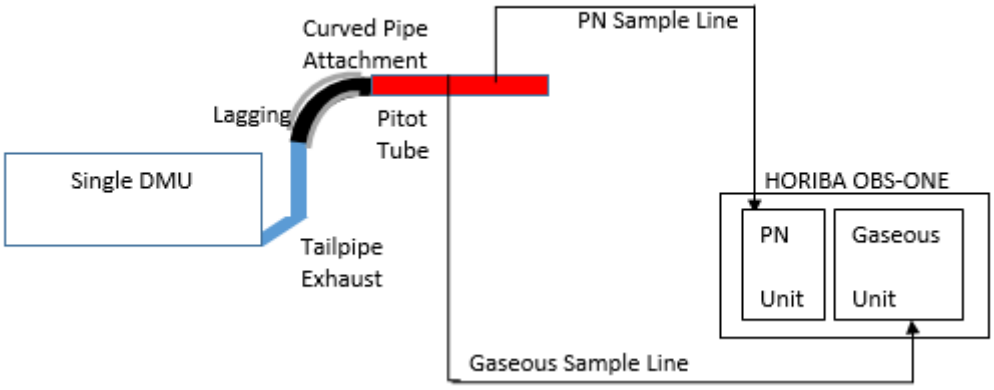


Figure 3.13 Apparatus for the exhaust sampling of a DMU train

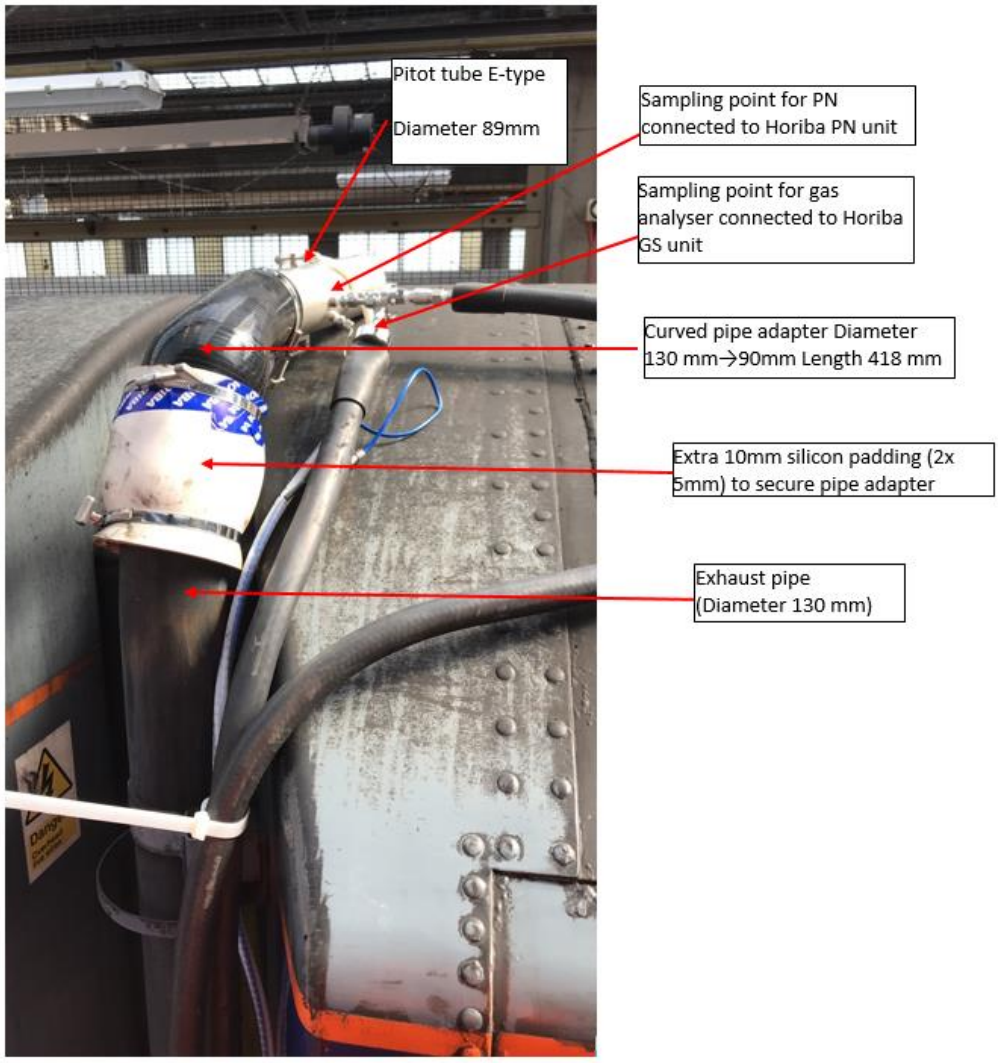


Figure 3.14 Exhaust sampling system on DMU train

3.4.2 PEMS specifications for the Horiba OBS-One system

Detailed specifications for the OBS-One unit are shown for the gas analyser unit (Table 3.6) and in Table 3.7 for the PN unit. NO_2 is measured as tailpipe pipe concentration. PN is measured particle number concentration (# cm^{-3}) from the exhaust pipe for the particles with a size range of 23-1000 nm.

Table 3.6 Horiba OBS-One Gas analyser specification (Horiba)

Name	**OBS-ONE-GS11**
Power Requirements	DC 22~28 V
Power Consumption(at stable state)	Approx. 0.45 kW

Dimensions	Approx. W 350 × D 470 × H 470 mm	
Weight (Main unit)	Approx. 45 kg	
Battery	Deep-cycle, sealed lead battery of DC 24 V 100 Ah（5 hour rate), Operation time ： Approx. 4.5 hours	
Operating Conditions	Temperature： -10 to 40 °C Relative humidity： less than 80%	
	Altitude： 0 to 2000 m above sea level	
Measurement Principle	**Measurement Range**	**Detection Range**
CO	Heated NDIR	0-0.5 to 0-10 vol%
CO_2	Heated NDIR	0-5 to 0-20 vol%
NO / NOx	Heated CLD	0-100 to 0-3000 ppm
NO, NOx, NO_2	Heated-dual CLD	0-100 to 0-3000 ppm
THC	Heated FID	0-100 to 0-10000 ppmC
Sampling Method	Wet measurement	-
Exhaust Flow Rate	Pitot flow meter	0-2.0 to 0-65.0 m^3 min^{-1}

Table 3.7 Horiba OBS-ONE PN unit specification (Horiba)

Name	**OBS-ONE-PN12**
Measuring Principles	Condensation particle counter (CPC)
Particle Diameter	23 ~ 1,000 nm
Measuring Range	0 ~ 5 × 10^7 particles cm^{-3}
Power Supply	DC 24 V
Power Consumption (Max.)	Approx. 0.25 kW
Mass	Approx. 18 kg
Operating condition	Temperature: -10 to 40 ℃ Altitude: 0 to 2000 m above sea level Relative humidity: less than 80% (No condensation)

3.4.3 Test procedure

The test procedure in Table 3.8 was designed to incorporate the typical maintenance procedure undertaken in the repair shed for the ‘run-up’ test with some modifications to include a greater run-time at each notch power setting, in which the trains are tested for fit-for-operation purposes. During the run-ups tests, white smoke is released from the exhaust, in particular at the higher notch settings. The results of the test will be used in the box model of Chapter 5 to estimate the rate of removal of NO_2 from the repair shed of the Neville Hill railway depot.

Table 3.8 Test procedure for exhaust emission measurement of Northern's train fleet in the repair shed

Step	Description
1	Begin test from cold-start, switch on engine at notch 0
2	Allow the engine to idle for 1 min at notch 0
3	Allow for air pressure to the brakes to build-up up to 4.5 bar pressure, the time to achieve this may vary between different trains, typically 5-7 minutes.
4	Change to notch 1, hold for 1 min
5	Change to notch 2, hold for 1 min
6	Change to notch 3, hold for 1 min
7	Change to notch 4, hold for 1 min
8	Change to notch 5, hold for 1 min
9	Change to notch 6, hold for 1 min
10	Change to notch 7, hold for 1 min
11	Change to notch 6, hold for 1 min
12	Change to notch 5, hold for 1 min
13	Change to notch 4, hold for 1 min
14	Change to notch 3, hold for 1 min
15	Change to notch 2, hold for 1 min
16	Change to notch 1, hold for 1 min
17	Change to notch 0, hold for 1 min
18	Switch off engine

3.4.4 PEMS data post-processing

The data gathered from the Horiba PEMS units as per the procedure of section 3.4.3 was second by second transient measurement data and requires post-processing. Firstly this involves averaging the individual concentrations at each notch power setting during a time period in the data, where the data was stable. This

can be done by assessing both acceleration and deceleration phases for each notch, and then choosing which between the two, has a more stable region for averaging the concentrations at each notch condition. These concentrations (ppm for CO, NO, NO_2 and NO_x and % for CO_2) can converted into mass flow concentrations. Equation 3.1 is used if the pollutant concentration is in ppm, whereas equation 3.2 is appropriate if the pollutant concentration is in vol% (CO_2).

$$m_i = \frac{[c]_i\ (in\ ppm)}{1E6} \times \rho_E \times q_e \times \frac{1000}{60} \quad (3.1)$$

where m_i is the mass emission rate of a given pollutant i in g s^{-1}, $[c]_i$ is the average concentration for a given pollutant i in ppm, ρ_E is the exhaust density in kg m^{-3}, q_E is the average exhaust volumetric flow rate for a given notch in m^3 min^{-1}.

$$m_i = \frac{[c]_i\ (in\ vol\%)}{100} \times \rho_E \times q_E \times \frac{1000}{60} \quad (3.2)$$

where m_i is the mass emission rate for a given pollutant (CO_2) in g s^{-1}, c_i is the average concentration for a given pollutant i (CO_2) in vol%, ρ_E is the exhaust density in kg m^{-3}, q_E is the average exhaust volumetric rate for a given notch in m^3 min^{-1}.

3.5 Well to Wheel analysis

In this study, the species of PM_{10}, NO_x and CO_2 are evaluated as part of WTT (Well to Tank) and WTW (Well to Wheel) assessments of red diesel, HVO, GTL and biodiesel fuels for a single DMU carriage. This is to address research question 3: What factors need to be considered when introducing biofuels into diesel-powered

trains?

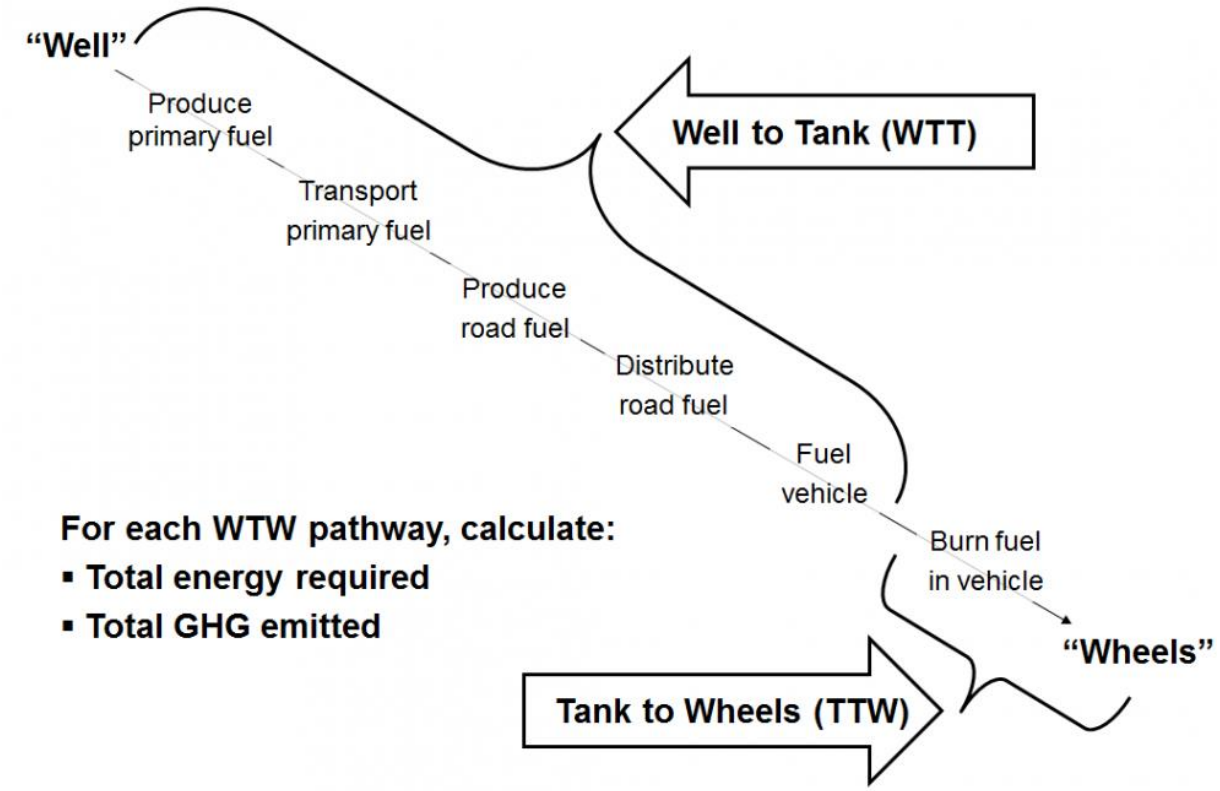


Figure 3.15 Well-to-Wheel flow chart for rail (EU, 2016)

GTL is considered for non-US natural gas feedstocks as well as GTL forming with and without a steam co-product. HVO is considered from 2 feedstocks: canola oil and used cooking oil animal fat. The functional unit is set as grams of CO_2 equivalent kWh $fuel^{-1}$ (g kWh^{-1}). The software package used is GREET following a review of a number of software packages capable of Well-to-Wheel analysis, and featured in the previous literature review chapter (section 2.5.3). The electricity mix during the extraction stage is set to a 2021 UK electricity power mix. For each of the species of interest, 4 life cycle stages are considered. These are: extraction, transport, production and combustion. The first 3 life cycle stages form the WTT and the last stage forms TTW (Tank to Wheel). By taking the total of the g kWh^{-1} contributions, across all 4 life cycle stages, the total WTW g kWh^{-1} is determined for each of the 3 species. In this study, the species are diesel, GTL and HVO. This will help with research question 3 in determining which factors need to be considered introducing alternative fuels into diesel-powered trains. The results of this are presented later in Chapter 4.

3.6 In shed temperature, humidity, NO, NO_2, NOx and $PM_{2.5}$ monitoring in the Neville Hill railway depot

Experiments are outlined for the assessment of in shed temperature, humidity and indoor air quality monitoring within the repair shed of the Neville Hill railway depot. This is in order to determine if there any variations in the concentrations of specific air pollutants such as NO_2, in the horizontal and vertical dimensions. These tie-in to research question 4, in which the factors affecting air quality are assessed.

In the vertical dimension, targeted measurements are conducted at one of the depots, Neville Hill, to investigate the presence of a temperature gradient within the main, maintenance shed, known as the repair shed. Experiments are outlined in section 3.4.4 and section 3.4.5 to support this. In section 3.4.4, the procedure for monitoring the change in NO_2 concentration with height over a one year period is outlined for investigating pollutant concentration gradients. Similarly, section 3.4.5 outlines the change of in shed ambient temperature with height over the same one year period. A temperature gradient within the shed is a problem, as it can potentially reduce the effectiveness of the ventilation extraction systems, by reducing the level of diesel fume extraction due to poor air mixing. In such circumstances, it is expected that both the in shed temperature and the pollutant concentration will increase with height, as noted in the indoor temperature gradient studies of MacCarty et. al for $PM_{2.5}$ and Johnson et. al for CO (MacCarty et al., 2020; Johnson et al., 2011).

Additional experiments for the transient measurement of air pollutions concentrations are covered for the horizontal dimension of Neville Hill's repair shed, with monitoring of $PM_{2.5}$ and transient NO (nitrogen monoxide), NO_2 and NO_x (nitrogen oxides). Transient $PM_{2.5}$ is monitored using a portable air quality monitor, which operates on the principles of a nephelometer, via light scattering measurement. Transient NOx is monitored using a Horiba APNA-370 chemiluminescence analyser. These transient concentrations will be used in Chapter 7, to determine compliance to the WEL (workplace exposure limits) values for NO and NO_2, and compared against the AQS for $PM_{2.5}$, NO and NO_2. The workplace exposure limit (WEL) standards relevant to this project are outlined in Table 3.9. These species include NO, NO_2 and respirable dust. The dust WEL is used as a rough comparison measure against the $PM_{2.5}$ concentrations for an 8 h TWA, due to a lack of a dedicated $PM_{2.5}$ WEL standard.

Table 3.9 Workplace exposure limits (WEL) for NO, NO_2 and dust (HSE, 2007; SCOEL, 2014; HSE, 2005a; HSE, 2005e)

Unit	NO	NO_2	Respirable Dust
	SCOEL/SUM/53/6/2014	SCOEL/SUM/89/6/2014	HSE EH40 2005
	8 h TWA	8 h TWA	8 h TWA
mg m^{-3}	2.5	0.96	4
ppm	2	0.5	

This section describes a series of experiments to address research question 4: 'What type of parameters affect the air quality of UK railway depots and train stations where diesel trains are in operation?'

3.6.1 Horizontal measurements of NO_2 with diffusion tubes in the in the repair shed of the Neville Hill railway depot

In this experiment, 13 diffusion tubes were installed at a height of 1.6 m in the repair shed of Neville Hill railway depot in Leeds, as seen in Table 3.8. These were divided over the 5 roads, with 3 diffusion tubes on each road, one at the East Entrance, one at the West Entrance and one in the middle of each road with a spacing between each tube of approximately 50 m. This mirrors the approach used in the Birmingham New Street study in which 3 diffusion tubes were placed on each platform with a 50 m lengthways spacing (Hickman et al., 2018a). In the Neville Hill railway depot, in a previous diffusion tube monitoring campaign, ESG Consultancy had placed three diffusion tubes on each road with a spacing of 36 m lengthways spacing (ESG, 2015).

Table 3.10 Gradko diffusion tube specification [58]

Parameter	Value
Type	50% TEA/Acetone
Limit of detection	Total NOx < 3 µg m^{-3} for 4 wk
Tube Length	71 mm
Internal diameter	11 mm
Recommended Exposure Period (wk.)	2-4
Air velocity, <10% wind speed (ms^{-1})	1-4.5
Shelf Life (wk.)	6
Relevant Standards	BS EN 13528 Parts 1-3: 2002/3

Parameter	Value
Desorption Eff.	0.98
Storage	Dark, cool environment, T= 5-10°C

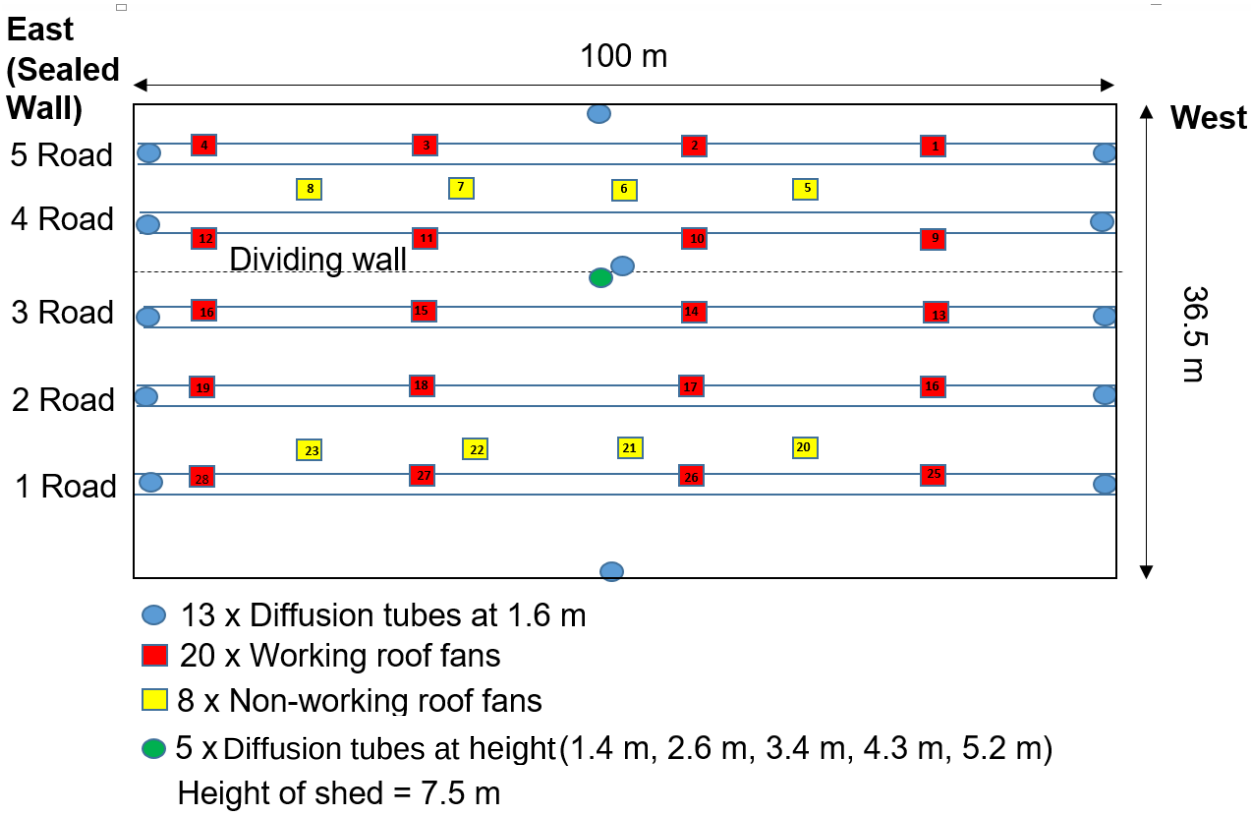


Figure 3.16 Layout of diffusion tubes within the repair shed of the Neville Hill railway depot

There are 20 operational fans in total, with 4 fans on each of the 5 roads (1-4, 9-12, 17-20, and 25-28). There are 8 additional locations which have non-operational fans. The results of this experiment will be later discussed in Chapter 6.

3.6.1.1 Diffusion tubes data post-processing

The diffusion tube concentration data was first averaged annually, as this is the unit of measure of the NO_2 AQS of 40 µg m^{-3} annual mean limit. This annualised data then needed to be corrected for bias by multiplying by a relative bias correction factor. In this study, a LAQM national bias correction factor of 0.89 is used, which corresponds to the same time period as this 1 year monitoring campaign between Apr 2018 and May 2019 (LAQM, 2021b). An uncertainty value of 24% is used for the individual 4 week data concentrations, with a 10% uncertainty used for annual NO_2

bias corrected concentrations derived from literature values of Bush (Bush et al., 2001).

3.6.2 Transient measurements of NO_x and $PM_{2.5}$ using an ambient chemiluminescence analyser (CLA) and an Airvisual Pro in the repair shed of the Neville Hill railway depot

In this experiment, transient air pollution measurement methods of NO, NO_2, NO_x and $PM_{2.5}$ are outlined for the centre of 3 Road in the repair shed of Neville Hill for 5 periods of 8 h on 5 consecutive days. The test period was between the hours of 7.30am and 3.30 pm for each of the 5 days. The species of NO, NO_2 and NO_x were monitored using a Horiba APNA-370 chemiluminescence analyser. $PM_{2.5}$ was monitored using an Airvisual Pro. The Horiba APNA-370 and the Airvisual Pro units were mounted on the top tier of a 3 tier trolley, as seen in Figure 3.17. On the second tier of the trolley, a zero air scrubber unit was positioned for zero gas calibration of the Horiba APNA-370 analyser.

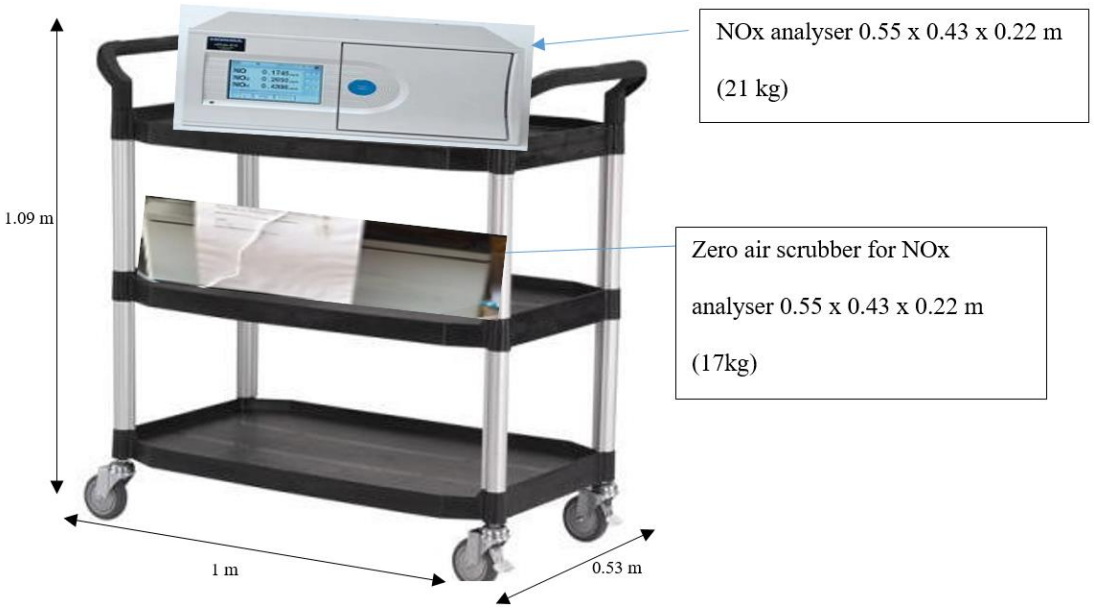


Figure 3.17 3 tier trolley with NO_x analyser and zero calibration scrubber

3.6.2.1 In-shed monitoring of NO, NO_2 and NO_x using a Horiba APNA-370 chemiluminescence analyser in the repair shed of the Neville Hill railway depot

The specification for the Horiba APNA-370 chemiluminescence analyser is provided in Table 3.11. Mounted on to a trolley, the Horiba analyser was positioned approximately 44 m from the East entrance and 54 m from the West Entrance as seen in Figure 3.18. There was a gap of 1.19 m width either side of the 3 tier trolley, to allow sufficient walkway space around the unit. Sampling was conducted at a height of 0.9 m from ground level via the sample point at the back of the Horiba APNA 370. A zero air scrubber was positioned on the middle tier of the trolley at 0.5 m from ground level, and was used for zero calibration prior to sampling. This arrangement can be seen later in Figure 3.20.

Table 3.11 Horiba APNA 370 specification

Model	APNA 370	
Range (Standard)	0 – 10 ppm	Automatic range switching
Range (Optical)	Max. 5 ranges between 0 and 0.1/10 ppm	Maximum range ratio:10
Minimum detection sensitivity (For ranges of ≤ 0.2 ppm)	0.5 ppb (2σ)	
Minimum detection sensitivity (For ranges of > 0.2 ppm)	0.5% (2σ) of the full scale	
Reproducibility	±1.0% of the full scale	
Linearity (readout error)	±1.0% of the full scale	
Zero drift	± 1.0% of the full scale /day	± 2.0% of the full scale /week (ambient temperature change: within 5°C)

Span drift	± 1.0% of the full scale /day	± 2.0% of the full scale /week (ambient temperature change: within 5°C)
Response	120 s or shorter (T_{90} from the inlet)	
Interference effect (Moisture)	Moisture 2.5%	Zero ± 2.0% of the full scale /day Span ± 3.0% of the full scale /day
Interference effect (NH_3)	NH_3 1 ppm	For ranges of 1 ppm or less ±4 ppb For ranges >1 ppm ± 1.0% of the full scale
Sample collection rate	~ 0.8 l min^{-1}	

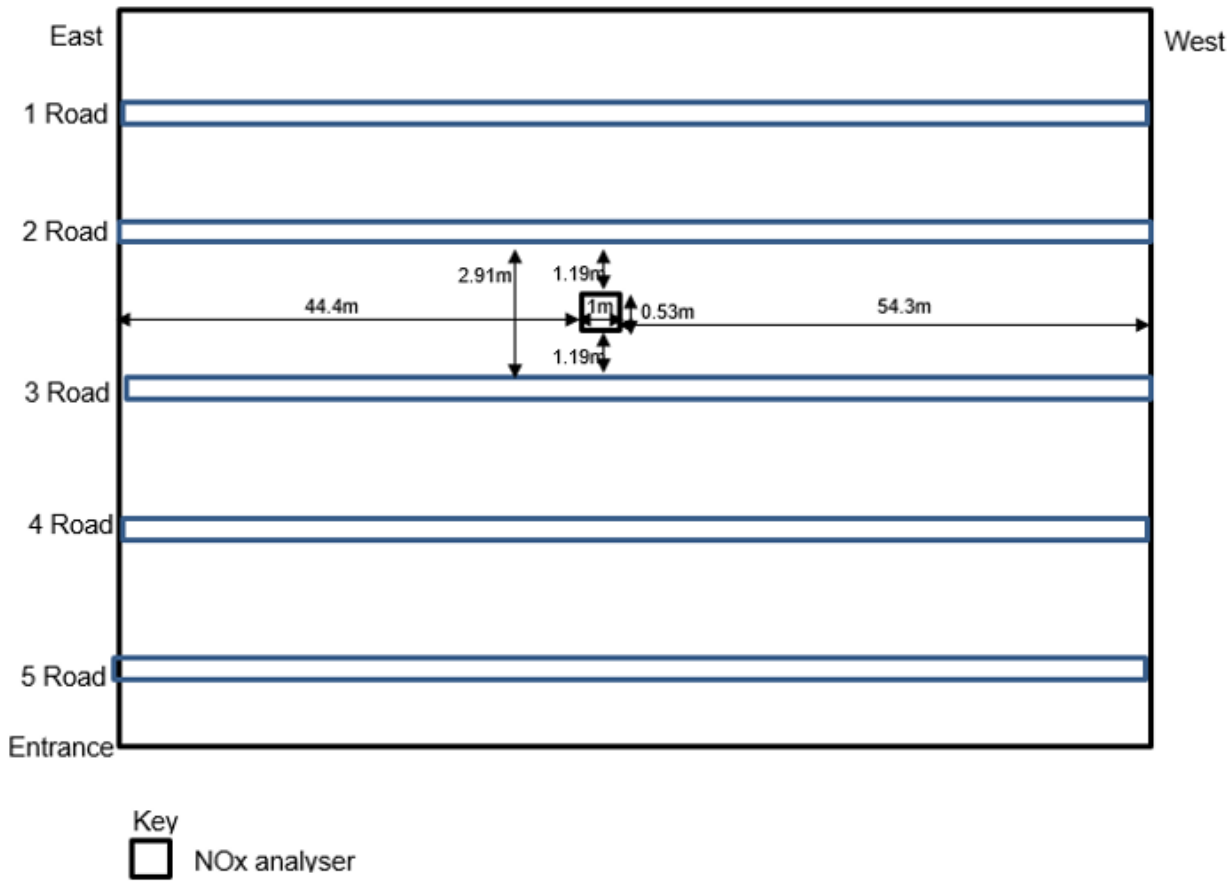


Figure 3.18 Location of the air quality monitoring equipment in the repair shed of the Neville Hill railway depot for transient NO_x and $PM_{2.5}$ measurement

3.6.2.2 In-shed monitoring of $PM_{2.5}$ using an Airvisual Pro in the repair shed of the Neville Hill railway depot

The Airvisual Pro is a portable air quality monitoring device as shown in Figure 3.19, which can measure $PM_{2.5}$, PM_{10}, CO_2, temperature and relative humidity. Its' operating principle is based on 'light scattering to measure particles and converting this signal into a mass concentration' (AQMD, 2015). The Airvisual Pro was also positioned on the same trolley as the Horiba APNA 370 on 3 road, but at a lower height of 0.5 m, as seen in Figure 3.20. A lower height was chosen for the Airvisual Pro to minimise tampering with the unit from depot staff.

Figure 3.19 Airvisual Pro for ambient $PM_{2.5}$ monitoring (IQAir)

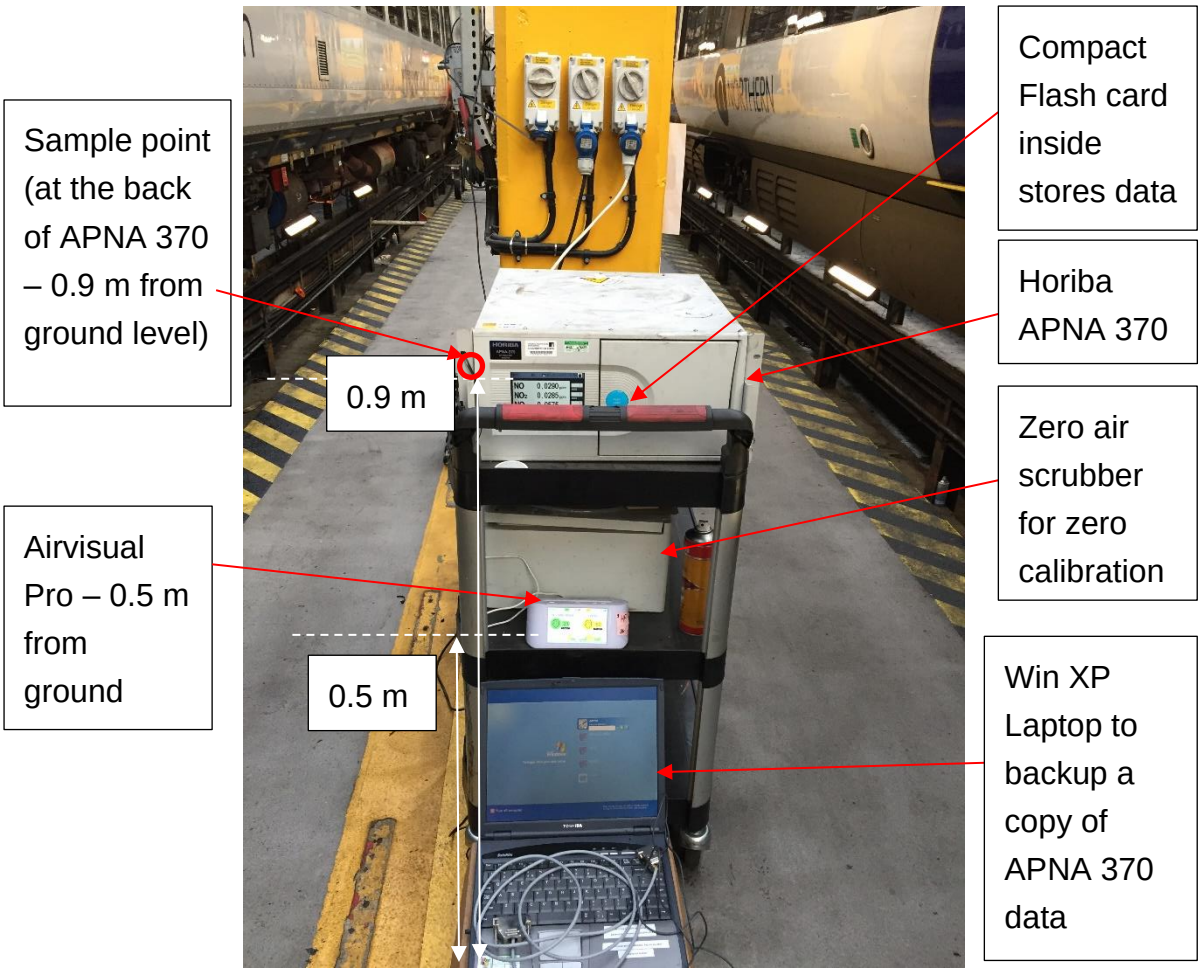


Figure 3.20 Airvisual Pro and Horiba APNA 370 NO_x chemiluminescence on 3 road in the centre of repair shed within the Neville Hill railway depot

Table 3.12 Specifications of Airvisual Pro

Dimensions	18.4 x 10 x 8.2 cm
Screen Size	12.7 cm LED screen
Battery Life	Approximately 4 hours on a single charge
$PM_{2.5}$ (Particulate Matter)	0.3 - 2.5 µm
Temperature	-10 to 40 °C
Humidity	0 - 95%
Logging interval	10 s to 3 h
PM range	0.3 – 2.5 µm

In field testing by the Brocza at the University of Leeds, the Airvisual Pro showed a slight overestimation of $PM_{2.5}$ concentrations with an $R^2 = 0.83$, as seen in Figure 3.28 (Brocza, 2019). This in agreement with similar measurements by Li et al. validating the accuracy of the Airvisual Pro, determining a $R^2 = 0.88 – 0.96$ for $PM_{2.5}$ when tested against 2 reference monitors, a GRIMM 11-C and a TSI SidePak (Liu et al., 2012; REPSS, 2022). The Air Visual also has low 'intra-model variability' for $PM_{2.5}$ as found by the South Coast AQMD (Air Quality Management District) in a co-location study with 3 AirVisual Pro units in close proximity to one another (AQMD, 2018). However, work by Brocza for PM_{10} found that there was a greater overestimation with measurements with the Airvisual Pro with an $R^2 = 0.56$ as seen in Figure 3.13 (Brocza, 2019).

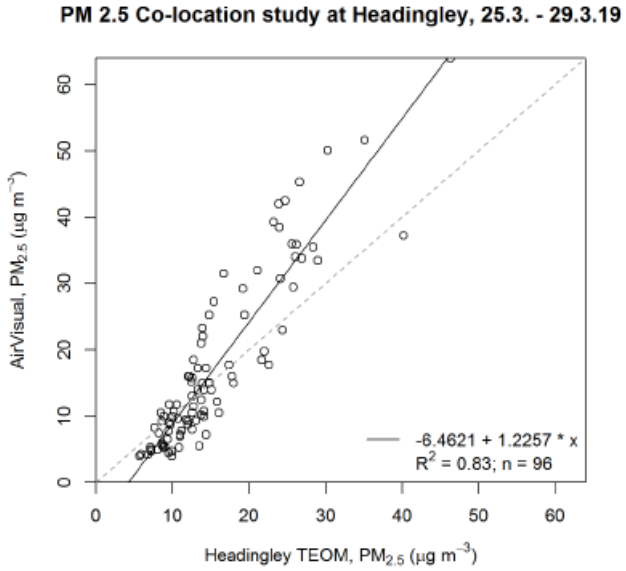


Figure 3.21 University of Leeds validation of $PM_{2.5}$ with Airvisual Pro against TEOM (Brocza, 2019)

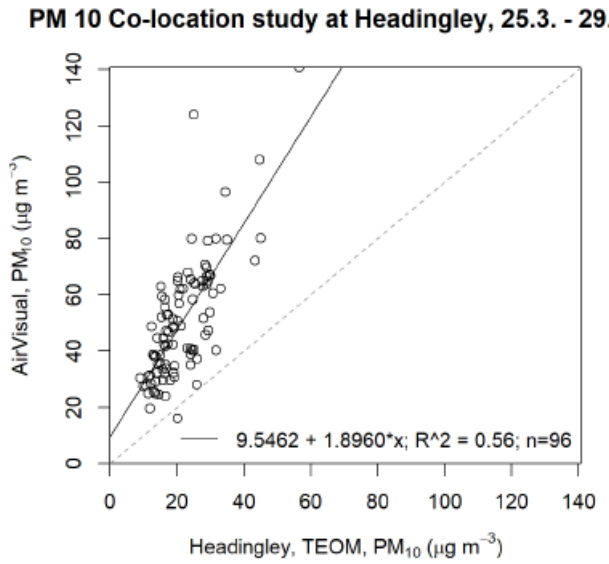


Figure 3.22 University of Leeds validation of PM_{10} with Airvisual Pro against TEOM

3.6.2.3 Transient NO, NO_2 and $PM_{2.5}$ data post-processing

3.6.2.3.1 Comparison against air quality standards

The NO, NO_2 and $PM_{2.5}$ measurements are subsequently averaged for comparison against air quality standards. In the case of NO and NO_2, the raw data on a 3 min timescale for NO and NO_2, is averaged over a 15 min time weighted averaged (TWA) period as per equation 3.3, as well as an 8 h TWA as per equation 3.4. This is for comparison against the 15 min STEL and 8 h TWA WELs. In addition for the NO_2 measurements, the NO_2 3 min timescale measurements are averaged over a 1 hour period for comparison against the UK AQS for NO_2. There is insufficient NO and NO_2 data to determine an annual concentration value for NO and NO_2 respectively, which prevents a direct comparison with the annual AQS for NO_2 of 40 µg m^{-3} (DEFRA).

$$[STEL] = \frac{\sum_1^n [X]_i \sum_1^n t_i}{15} \quad (3.3)$$

where [STEL] is the time weighted average (15 min) for a particular pollutant X in mg m^{-3} or ppm, $[X]_i$ is the exposure or concentration of X at duration i in mg m^{-3} or ppm, t_i is the duration of the measurement for pollutant X

$$[TWA] = \frac{\sum_1^n [X]_i \sum_1^n t_i}{8} \quad (3.4)$$

where [TWA] is the time weighted average (8 h) for a particular pollutant X in mg m^{-3} or ppm, $[X]_i$ is the exposure or concentration of X at duration i in mg m^{-3} or ppm, t_i is the duration of the measurement for pollutant X

For the $PM_{2.5}$ measurements the raw data is averaged over an 8 hour period as per equation 3.2 for comparison against the dust 8 h TWA WEL of 4 mg m^{-3} (HSE, 2005b).

3.6.2.3.2 Determining which variables contribute most to indoor NOx and $PM_{2.5}$ concentrations

To support research question 4, in determining the parameters affecting air quality, multivariate linear regression was used for determining the relationship between a number of dependent variables affecting the concentration of a given pollutant and a single independent variable, the concentration of a single pollutant. This is conducted firstly for NO_x as the independent variable, as seen in equation 3.3 and then secondly with $PM_{2.5}$ as the independent variable as seen in equation 3.4. In this study, the dependent variables are the number of individual carriages of each of the train types present within the repair shed of Neville Hill railway depot as well an additional dependent variable for ambient indoor temperature. The multivariate linear regression was computed using the R software package.

The reasons for choosing multivariate linear regression for this study is that it is an easy-to-setup method and can be used indicatively to estimate which DMU is contributing the most to the indoor pollutant concentrations within the repair shed of the Neville Hill railway depot. Time constraints in this study limited the use and exploration of other regression methods in this study. Multivariate linear regression assumes a linear relationship between each of the dependent variables and the independent variables. It does however, however, in a simplified form, discount the effects of collinearity between variables. For the purpose of this study, collinearity effects are classified outside of the scope of this study. Some suggestions have been included in the future work section how the reader, can use more complex methods to conduct regression analysis with collinearity effects.

The regression equation describing the attribution of indoor temperature (T) and the number of trains (N) of a specific train type to the indoor NOx concentration is given in equation 3.5.

$$[NO_x] \sim x_1T + x_2N150 + x_3N153 + x_4N155 + x_5N158 + x_6N170 \quad (3.5)$$

where $[NO_x]$ is the concentration of NO_x in µg m^{-3}, T is the indoor temperature, N150 is the number of individual train carriages of the 150 train, N153 is the number of individual train carriages of the 153 train, N155 is the number of individual train carriages of the 155 train, N170 is the number of individual train carriages of the 170 train, x_i is the regression coefficient for each of the dependent variables where i = 1, 2,…n

This procedure is then repeated for $[PM_{2.5}]$ using the regression equation of equation 3.6.

$$[PM_{2.5}] \sim x_1T + x_2N150 + x_3N153 + x_4N155 + x_5N158 + x_6N170 \quad (3.6)$$

where $[PM_{2.5}]$ is the concentration of $PM_{2.5}$ in µg m^{-3}, T is the indoor temperature, N150 is the number of individual train carriages of the 150 train, N153 is the number of individual train carriages of the 153 train, N155 is the number of individual train carriages of the 155 train, N170 is the number of individual train carriages of the 170 train, x_i is the regression coefficient for each of the dependent variables where i = 1, 2,…n

3.6.3 Measurements at different heights of NO_2 with diffusion tubes in the repair shed of the Neville Hill railway depot

In this experiment, 5 diffusion tubes were installed in the centre of the depot on 3 Road at heights of 1.4 m, 2.6 m, 3.4 m, 4.3 m and 5.3 m in the repair shed of the Neville Hill railway depot as seen in Figure 3.23. Tinytag temperature and relative humidity devices were placed at this same location at the 5 corresponding heights as seen in Figure 3.23. The diffusion data were processed as per the same procedure of section 3.6.1.1.

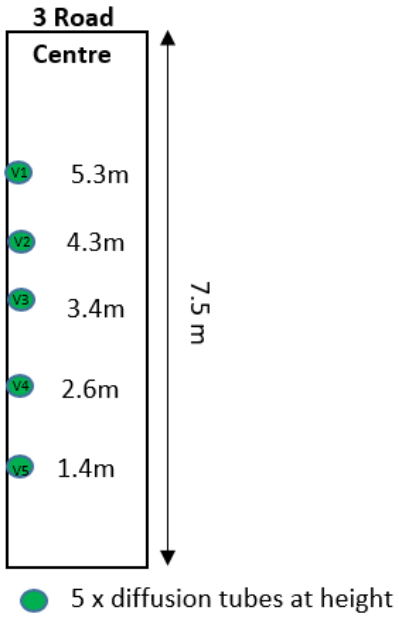


Figure 3.23 Layout of diffusion tubes at height within the repair shed of the Neville Hill railway depot

3.6.4 Measuring the vertical temperature and humidity profile in the repair shed of the Neville Hill railway depot

In this experiment, 5 Tinytag Radio devices were co-located with the diffusion tubes at height, as seen previously in Figure 3.23. The Tinytag devices monitor in-shed temperature and relative humidity, with specifications provided in Table 3.13. These devices operate wirelessly via a radio-frequency, bridging modem, and allow for the temperature and relative humidity data to be obtained from a safe, office location. The location for the tinytags is attributed to discussions with the depot staff who identified the middle of 3 Road as the highest zone of activity in the repair shed. The Tinytags were placed at 1.4 m, 2.6 m, 3.4 m, 4.3 m and 5.3 m respectively, as indicated in Figure 3.23.

Table 3.13 Tinytag specification(Tinytag, 2017)

Name	Tinytag Plus Radio
Model No.	TRGF-4500
Type	Outdoor
Measures	Temperature, relative humidity
Unit Cost	£325

Dimensions (mm)	241 x 155 x 62
Range	-25 to 85°C 0-100 %RH
Battery Life	1 yr
Accessories required	ACSRF-4040-PK Receiver + Software (£700)
Log Interval	2 mins – 10 days
Storage	Minimum 2 weeks using 10 min log interval (offline storage)
Range	200m
Weight	554 g (standalone)
Tech	Radio (Device) + Ethernet/Wi-Fi (Receiver)
Resolution	0.02 °C or better

The temperature data gathered at height over a 1 year period were averaged using a diurnal hourly average to observe the changes in temperature with height over a 24 hour period.

3.7 NO_2 monitoring in the depots of Allerton, Newton Heath and Heaton

In this section, experiments are outlined for similar horizontal measurements of NO_2 concentrations within the 3 railway depots of Allerton, Newton Heath and Heaton, as well as Neville Hill's other maintenance shed (service shed), utilising diffusion tubes in a similar manner to section 3.6.1.

3.7.1 Horizontal and vertical measurements of NO_2 with diffusion tubes in the 3 depots of Allerton, Newton Heath and Heaton

In this experiment, within each of the three railway depots, diffusion tubes were first installed at 3 positions on each road at ground level. In addition for each depot, 3 tubes were installed at height in the centre of each depot. These were installed for a 6 month period, corresponding to 15 diffusion tubes in the Allerton

railway depot (Figure 3.24), 19 tubes in the Newton Heath depot (Figure 3.25), 17 diffusion tubes in the Heaton railway depot (Figure 3.26) and 7 diffusion tubes in the service shed of the Neville Hill railway depot (Figure 3.22). Similar to section 3.4.3, three additional diffusion tubes were placed at height in the Allerton (1.6 m, 3.2 m and 4.9 m), Newton Heath (1.6 m, 2.8 m and 5.6 m) and Heaton (1.6 m, 2.5 m and 5 m) railway depots to monitor changes in NO_2 concentration with height. The results of this experiment will be later discussed in Chapter 5. The diffusion data were processed as per the same procedure of section 3.6.1.1.

3.7.1.1 Diffusion tube measurements of NO_2 in the Allerton railway depot

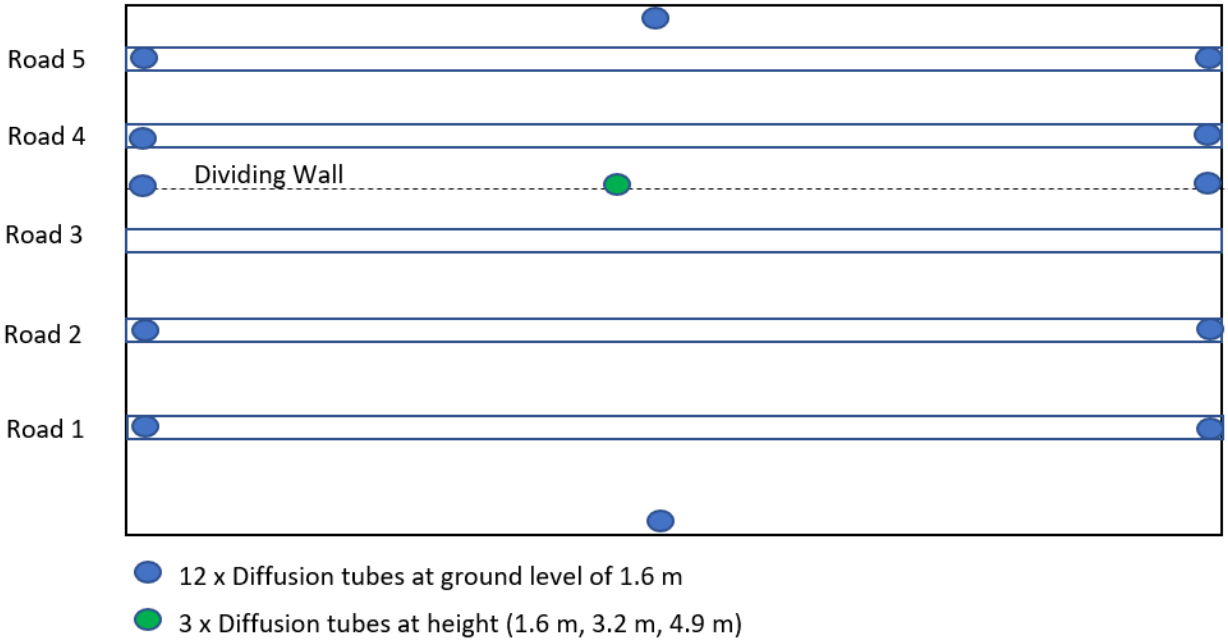


Figure 3.24 Layout of diffusion tubes within the main shed of the Allerton railway depot

3.7.1.2 Diffusion tube measurements of NO_2 in the Newton Heath railway depot

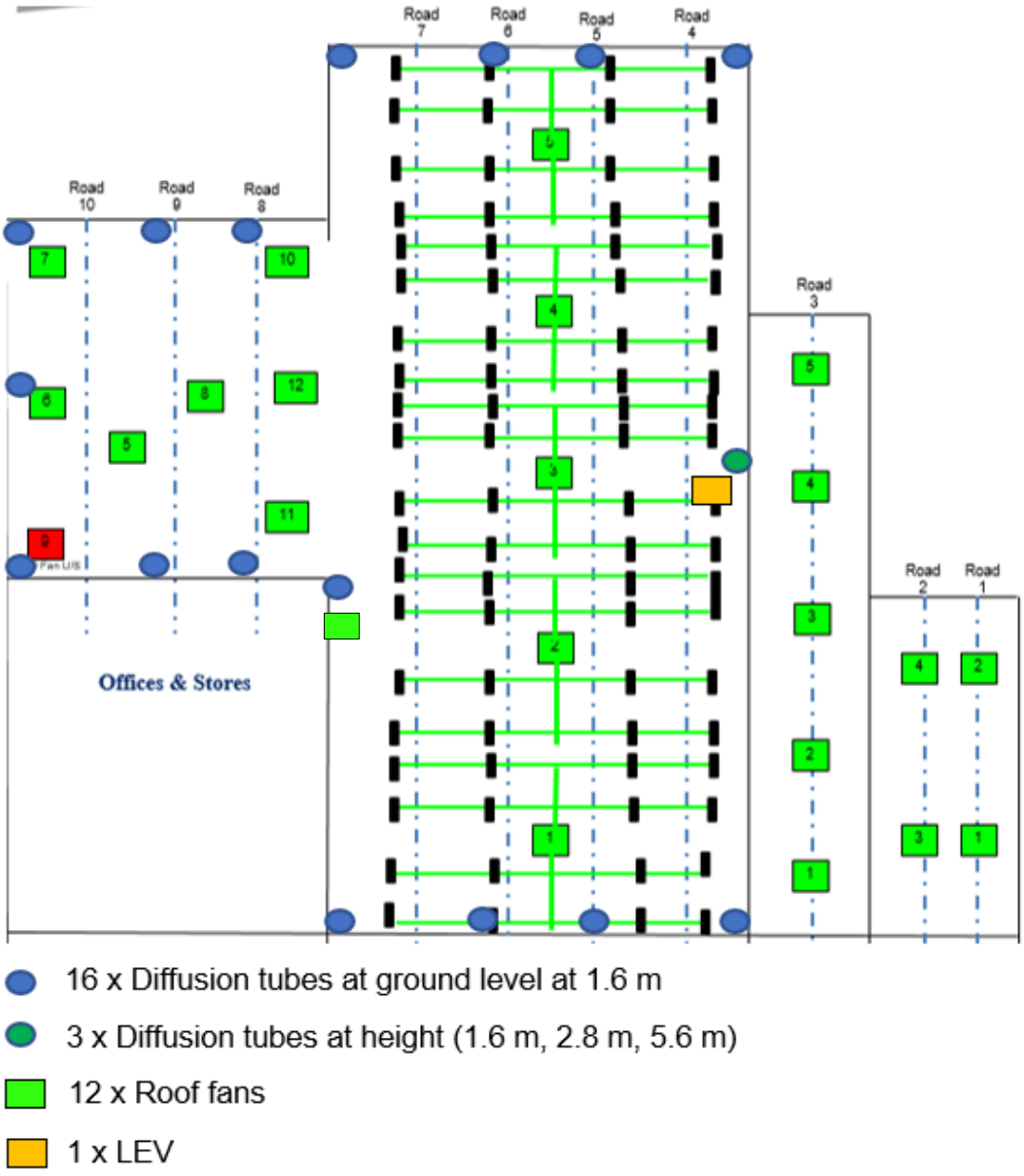


Figure 3.25 Layout of diffusion tubes within the main shed of the Newton Heath railway depot

3.7.1.3 Diffusion tube measurements of NO_2 in the Heaton railway depot

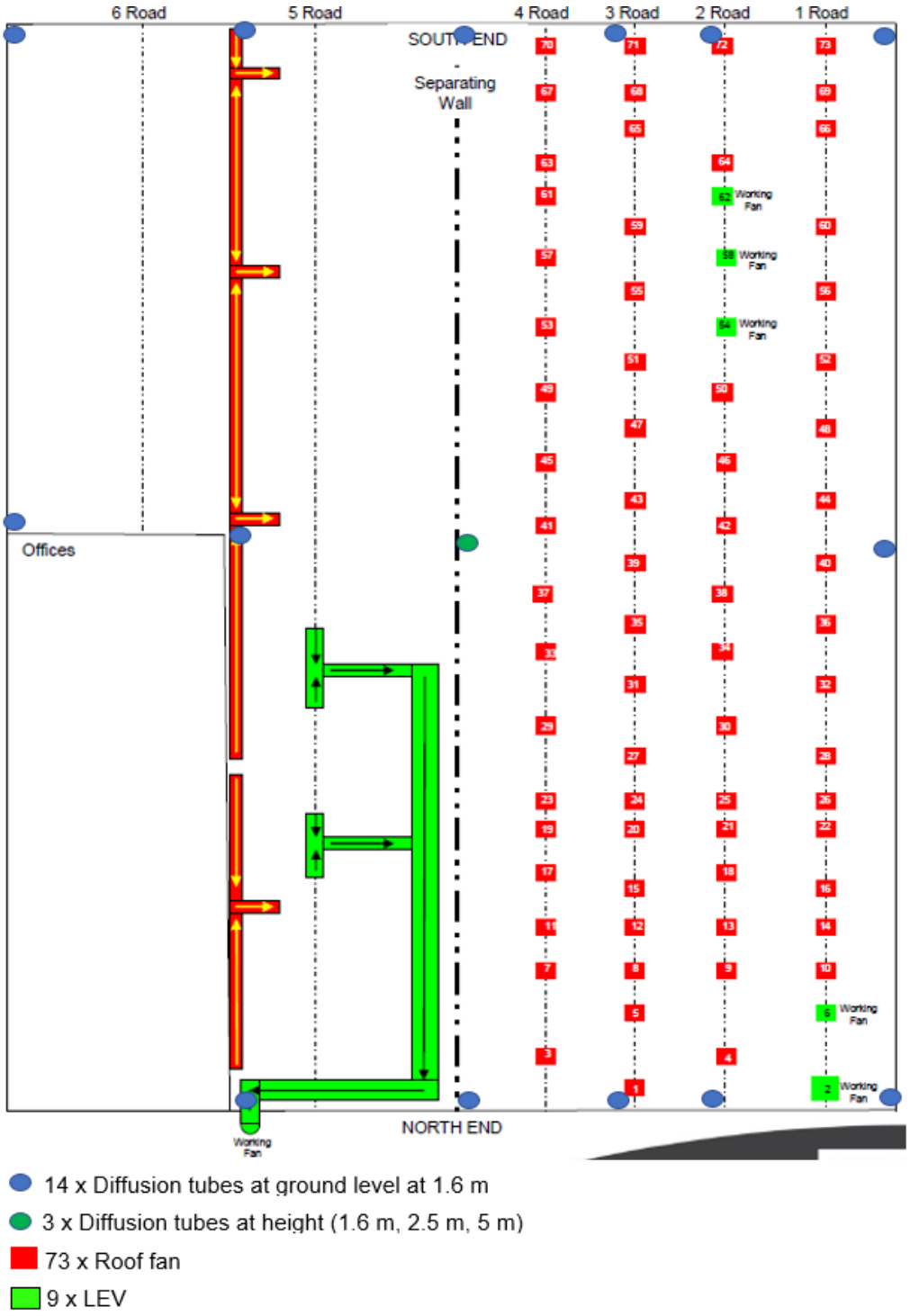


Figure 3.26 Layout of diffusion tubes within the main shed of the Heaton railway depot

3.7.1.4 Diffusion tube measurements of NO_2 in the Service Shed of the Neville Hill Railway depot

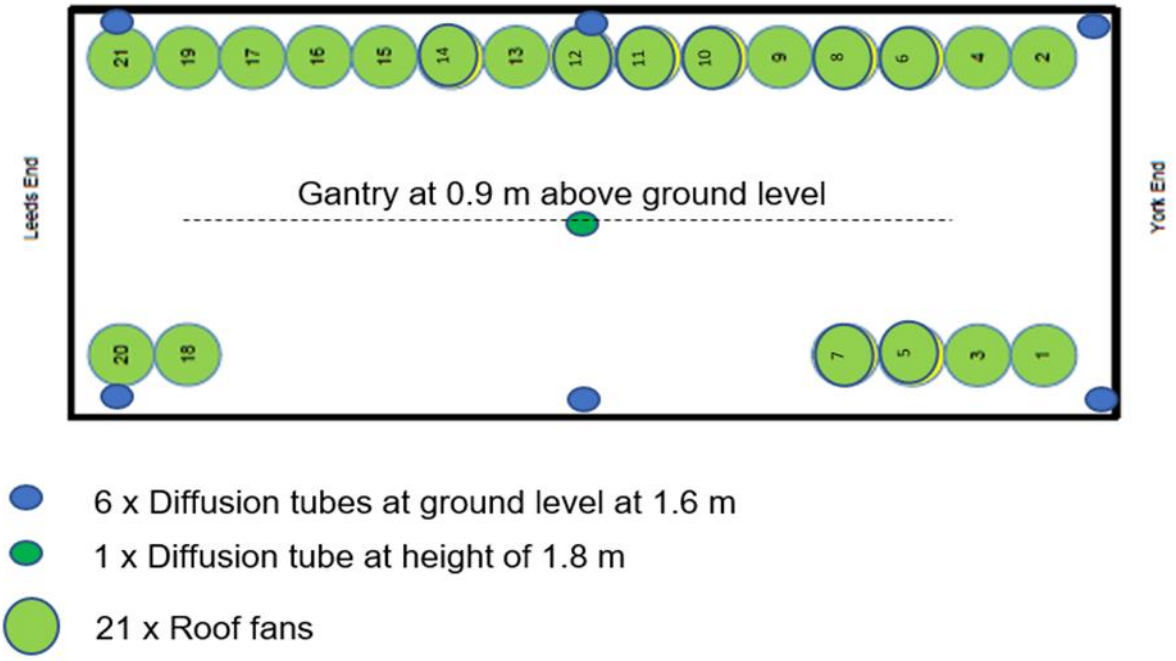


Figure 3.27 Layout of diffusion tubes within the service shed of the Neville Hill Railway depot

3.8 NO_2 monitoring in the Manchester Victoria station

In this experiment, 21 diffusion tubes were installed at a height of approximately 2.5 m in Manchester Victoria station to monitor the NO_2 concentrations with the station, both at ground level and in a targeted area at changing height. These were divided over the 6 platforms, with 3 diffusion tubes placed at head height on each road, one at the West End, one at the East End and one in the middle of each platform (where possible) with a spacing between each tube of approximately 100 m as shown in Figure 3.23. This layout was chosen to mirror a similar approach utilised in the Birmingham New Street study with 3 diffusion tubes on each platform with a 50 m spacing between each diffusion tube (Hickman et al., 2018a). In addition, 3 additional diffusion tubes were placed within the overbridge to assess the effect of trains parked underneath the overbridge, on the NO_2 concentrations inside the overbridge. By installing diffusion tubes at both ground level and within the overbridge section, this will help to assess the influence of trains on passenger exposure both on the platform and in transit over the bridge. This supports research

question 4, identifying parameters which affect air quality within a train station. The results of this experiment will be later discussed in Chapter 5. The diffusion data were processed as per the same procedure of section 3.6.1.1.

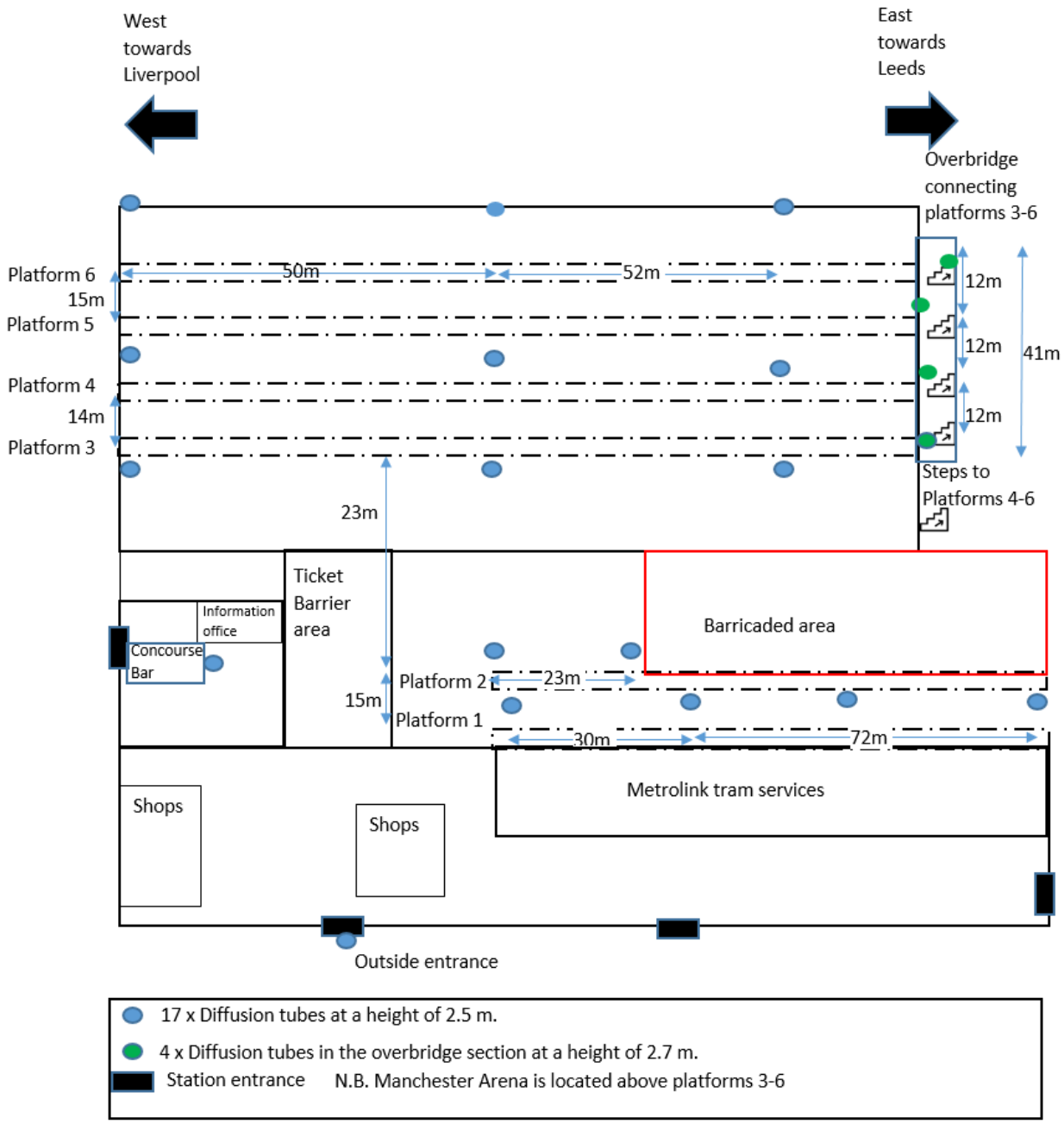


Figure 3.28 Layout of diffusion tubes within the Manchester Victoria station

3.9 Box model

A box model can be used to predict the concentration of an ambient pollutant over a theoretical box (CIBSE). It assumes that the pollutant concentration is at steady-state conditions within the box, with the pollutant concentration, the same at all points within the box model, due to a well-mixed box. This is important for this study, as this study will test the well-mixed nature of one of the railway sheds, known as the 'repair shed', located with the Neville Hill railway depot (De Nevers, 2000). The box model will be used in this study to test the validity of the number of air changes estimated by an external consultant for the repair shed, at 6 ACH under well-mixed conditions. The presence of a temperature gradient within the repair shed, will indicate incomplete mixing, and that the number of air changes will consequently be lower, than 6 ACH.

The box model used for this study is presented in equation 3.7 and is based on a box model equation derived by MacCarty et al. MacCarty et al.'s box model was developed for an indoor kitchen environment with an indoor cookstove as a point source. This is similar to the circumstance within the depot with the trains acting as point sources, within an indoor building.

$$[NO_2]_{t+1} = [NO_2]_{\mathrm{t}} + \frac{1000\ \mathrm{f}\ q_{NO_2}}{V} + \frac{\propto([NO_2]_b - [NO_2]_{\mathrm{t},})}{60} \quad (3.7)$$

where $[NO_2]_{t+1}$ is the concentration of NO_2 introduced at a constant rate into a fixed volume at time t+1, V is the volume of the shed in m^3, q_{NO_2} is the source emission rate of NO_2 in mg min^{-1}, f is a dimensionless parameter indicating ratio of emissions that make it into the room due to effectiveness of chimney in the MacCarty et al. study where f=1 means no chimney is present, 0 means chimney totally removes emissions, $\propto$ is the air exchange rate in h^{-1}, $[NO_2]_b$ is the background concentration of NO_2 , V is the volume of the ventilated space (L $s^{-1)}$, $[NO_2]_{\mathrm{t}}$ is the concentration of NO_2 introduced at a constant rate into a ventilation space of volume at time t.

3.9.1 Ventilation data for the repair shed of Neville Hill

The external contractor, ESG Consultancy had conducted ventilation rate measurements underneath the fans with the repair shed of the Neville Hill railway depot on the 6th November, 2015. This study measured vertical velocity using an AM5000 high speed anemometer. Measurements were taken by taking a 'traverse in each direction across the fan'. This procedure was repeated for the 28 fans in the repair shed (ESG, 2015).

Table 3.14 Ventilation fan speed for Neville Hill repair shed (ESG, 2015)

	CSA	Velocity	Quantity	Quantity	Quantity	Volume
	m^2	$m\ s^{-1}$	$m^3\ s^{-1}$	$m^3\ min^{-1}$	$m^3\ h^{-1}$	$l\ h^{-1}$
Fan 1	0.42	4.4	1.8	111	6638	6637680
Fan 2	0.42	6.2	2.6	156	9374	9374400
Fan 3	0.42	7.0	2.9	177	10599	10599120
Fan 4	0.42	7.1	3.0	178	10660	10659600
Fan 9	0.42	6.9	2.9	175	10478	10478160
Fan 10	0.42	7.0	3.0	177	10644	10644480
Fan 11	0.42	7.1	3.0	179	10720	10720080
Fan 12	0.42	7.0	3.0	177	10644	10644480
Fan 13	0.42	7.8	3.3	196	11763	11763360
Fan 14	0.42	7.5	3.1	188	11280	11279520
Fan 15	0.176	22.2	3.9	233.9	14034	14034240
Fan 16	0.42	7.1	3.0	180	10781	10780560
Fan 17	0.42	7.3	3.1	183	10977	10977120
Fan 18	0.42	7.2	3.0	182	10902	10901520
Fan 19	0.176	23.0	4.1	242.9	14573	14572800
Fan 20	0.42	6.9	2.9	175	10493	10493280
Fan 25	0.42	7.2	3.0	180	10826	10825920
Fan 26	0.176	13.0	2.3	137	8237	8236800
Fan 26	0.176	12.0	2.1	127	7591	7590528
Fan 27	0.42	7.5	3.1	188	11280	11279520
Fan 28	0.42	6.9	2.9	175	10478	10478160
Total			**61.9**	**3716**	**222971**	**222971328**

where CSA: Cross-sectional area of fan

For the Neville Hill railway depot, using the information from Table 3.14, the total extraction rate is estimated to be 222971 $m^3\ h^{-1}$ (ESG, 2015) This information can help estimate the indoor NO_2 concentration, $[NO_2]_{t+1}$ as described earlier in equation 3.7.

3.10 Quality Assurance

3.10.1 Diffusion tubes

The average diffusion concentration should be corrected for relative bias using a bias adjustment factor. There are two types of bias factor as described in TG22 guidance from DEFRA and Diffusion Tube Practical Guidance from AEA on behalf of DEFRA:

1. National relative bias adjustment factor (CF_b). This is a bias adjustment factors determined from previous studies in the UK and stored in a LAQM database.

2. Locally determined bias factor (CF_l). This is determined on an individual site by the co-location of triplicate diffusion tubes spaced 10 cm spacing apart and 1 m away from a NO_x chemiluminescence analyser, for a period of at least 9 months (LAQM, 2022a; AEA, 2008c)

The relative bias corrected annualised mean period concentration, [BD1] is determined through equation 3.8.

$$[BD1] = [d] \times CF_b \quad (3.8)$$

where [BD1] is the national relative bias corrected annualised mean period concentration, [d] is the diffusion tube concentration in μg m^{-3} and CF_b is the national relative bias correction factor.

As per LAQM TG22 guidance, “for a strict comparison [against the AQS] there should be a minimum of 85% data capture throughout a calendar year. If there is less than 85% data capture, the bias corrected annualised concentration should be expressed as a percentile of annual roadside standard” (LAQM, 2022b).

In this study, a relative national bias correction factor of 0.89 is used for the diffusion tubes in this study, which is obtained from the national LAQM bias correction factors database for the 2018-19 period (LAQM, 2021b). It must be noted that the national bias factors collated by the LAQM are derived from outside, roadside locations. The national bias factors have been utilised with a caveat in this study to correct the diffusion tube data from an indoor, railway depot environment, following

dialog with the LAQM (Stockton, 2020). Hickman's local bias adjustment factor of 0.89 ± 0.02 for the Birmingham New Street train station, coincidentally is the same as the 0.89 national bias factor used for this study, further justifying the use of 0.89 as a bias factor (Hickman et al., 2018b).

3.10.2 Chemiluminescence analyser

For continuous monitoring, zero and gas calibration checks were conducted prior to measurement as per TG22 guidance and the local site operator (LSO) manual (Ricardo, 2012; LAQM, 2022b). For data analysis of the concentrations obtained from the analyser, outlier identification was conducted using the approach of Balogun et al. (Balogun et al., 2010) in which a screening criteria of mean ± 3 σ was applied for the NO, NO_2 and NO_x raw data concentrations. For NO_x, this upper threshold was set at 0.25 ppm (478 µg m^{-3}) on a 3 min timescale.

3.10.3 Air Visual Pro

As the AirVisual Pro, is not a MCERTS rated unit for PM Measurement, a correction factor was applied to the PM_{10} concentration from a previous study which determined a relative bias correction factor of 0.83 following a co-location study with a TEOM. Outlier identification was conducted using the same Balogun et al. approach as the chemiluminescence analyser, with a screening criteria of mean ± 3 σ (Balogun et al., 2010). Due to the tendency for the AirVisual to occasionally spike unnecessarily, unrelated to train movements, an additional threshold of designating $PM_{2.5}$ concentrations greater 200 µg m^{-3} on a 10 s timescale, as outliers was introduced.

3.10.4 TinyTag

The indoor temperature data obtained from the Tinytag devices, at 10 min intervals, were quality assured by a statistical screening criteria of the hourly mean ± 3σ i.e. 10 min temperature data points that were either above or below the hourly mean ± 3σ, were screened out (0.2% of data). After quality assurance, the temperature data points were averaged to four weekly intervals to align with the same period as the diffusion tube measurements in the repair shed.

3.10.5 Error Analysis

Error bars are used for the correction of the experimental measurements outlined for the NO_2 diffusion tubes of section 3.41, 3.44, 3.5.1 and 3.6. This is done using an uncertainty value of ± 24%, which is at the lower end of range of uncertainty values (± 24-38%) determined by Bush for the uncertainty of a single diffusion tube (Bush et al., 2001). For the annualised diffusion tube concentration, an uncertainty value of ± 10% is used, which is at the lower end of range of uncertainty values (± 10-18%) also determined by Bush for uncertainty for diffusion tube over a 1 year period (Bush et al., 2001). For the rail exhaust emission measurements outlined in section 3.7, the uncertainty in the exhaust concentration measurements are estimated at 15% based on literature data from Varella which tested the error difference between a PEMS unit and a laboratory reference using a light duty engine (Varella et al., 2018). For this study, the light duty data will be used as a proxy for heavy duty vehicles. The uncertainty in the volumetric flow for the Horiba PEMS unit is estimated at ± 10% derived from literature data by Varella (Varella et al., 2018). The uncertainty in PN is estimated at ± 30% based on literature data from the JRC (Joint Research Council) (Giechaskiel et al., 2016). The mass flow rate uncertainty is determined at ± 18%, calculated as the product of the concentration and volumetric flow rate, using the propagation of error formula of equation 3.9.

$$\Delta Z = \sqrt{\Delta X^2 + \Delta Y^2} \tag{3.9}$$

where ΔX is the change in exhaust concentration uncertainty, ΔY is the change in volumetric flow rate uncertainty and ΔZ is the change in mass flow rate uncertainty.

3.11 Conclusion

Overall, Chapter 3 outlines the methods to conduct a combination of field based experiments and desk based modelling for the investigation of air quality and decarbonisation in 5 locations in the rail sector, which will be later applied within the later chapters of this thesis. A number of experiments are outlined to assess the rail vehicle exhaust emissions in a depot, indoor depot air quality, ventilation effectiveness and life cycle contributions of individual air pollutants and CO_2 for diesel rail engine fuels. The work of this project aligns with wider work by the RSSB in rail air quality and rail emissions research as noted in their Air Quality Strategic Framework, to meet the rail air quality improvement ambitions of the UK Clean Air Strategy 2019 pertinent to the rail sector (RSSB, 2020; DEFRA, 2019).

Chapter 4 Static train tailpipe exhaust emission measurements in a UK railway depot

4.1 Overview

This chapter assesses the tailpipe exhaust emissions from three DMU (Diesel Multiple Unit) carriages (150142, 153378 and 158903) operated by Northern Rail in order to address research question 1 in sub-section 4.2:

R1: What are the emission levels of Northern Rail DMUs in a railway depot, and how do these emissions compare to other vehicles?

In addition, the WTW (Well-to-Wheel) life cycle impacts of replacing diesel fuels in a typical DMU vehicle with alternative fuels, such as HVO and GTL will also be evaluated in order to address research question 2 in sub-section 4.3:

R2: What are the WTW life cycle impacts which need to be considered when introducing alternative fuels into diesel-powered trains?

A brief review of the factors which affect the introduction of alternative fuels will also be conducted answering research question 3 in sub-section 4.4:

R3: What factors need to be considered when introducing alternative fuels into diesel-powered trains?

4.2 Evaluation of the emission levels of Northern Rail DMUs in the Neville Hill railway depot

Rail exhaust emission tests were conducted in collaboration with Horiba UK between the 4th to the 8th June, 2018 at the Neville Hill railway depot in Leeds. 3 DMUs were tested inside the repair shed building of the railway depot, using a Horiba OBS-One PEMS (Portable Emission Measurement System). The DMUs were parked within the repair shed and tested at steady state conditions for the measurement of a number of species and parameters from each of the 3 DMUs. These included: NO (nitrogen monoxide) concentration in ppm, NO_2 (nitrogen dioxide) concentration in ppm, NO_x (nitrogen oxides) concentration in ppm, CO (carbon monoxide) concentration in ppm, THC (total hydrocarbons) concentration in ppmC, CO_2 (carbon dioxide) concentration in %vol, PN (particle number) in # cm^{-3}, T_e (exhaust temperature) in °C and q_e (exhaust volumetric flow rate) in m^3 min^{-1}. Low

sulphur diesel, was the fuel used within all 3 of the DMUs tested in this study. The test conditions deployed in this study, were designed to simulate representative operation of DMUs in a railway depot, with some minor modifications to obtain longer time measurements on each notch.

The 150142, 153378 and 158903 DMUs, also known as 15X DMUs, were tested with the engines of the DMUs started from cold-start at notch 0, and held for 1 min, following which, an additional 3-5 mins was spent on the same notch 0, to allow the air pressure to the brakes to build up to 4.5 bar, where this air pressure build allows a switch from a parking brake, which the train is initially on, to full service brakes, a pre-requisite for engine operation above notch 0. After this pressure was reached, the notch position was increased by an increment of one notch each time, up to full power at notch 7, in which the gear shift was held at 1 min for each of the 15X DMUs. After being held at the maximum notch power setting, of notch 7 for 1 min as described previously, the gear shift was then decreased by 1 notch, and held for 1 min at each of the notch power settings between notch 6 and notch 0, for a period of 1 min with the 15X DMUs.

4.2.1 Exhaust emission measurement of a number of diesel DMUs using a PEMS (Portable Emission Monitoring System) in the Neville Hill railway depot

The DMUs selected in this study for exhaust emission measurement were chosen, as they make-up the 24% of Northern Rail's rail train fleet, as of 2019 (DfT, 2017). The DMUs in this study have no diesel aftertreatment systems, with a brief specification for each DMU provided in Table 4.1. Retrofit technologies are available to reduce the concentrations of diesel exhaust emission species, and include SCR (Selective Catalytic Reduction), DOC (Diesel Oxidation Catalyst) and DPF (Diesel Particulate Filter). SCR is a system for NO_x reduction and can reduce NO_x emissions by up to 99% (Yara, 2021; Agriemach, 2022; Carlisle, 2017). DOC is designed for CO and UHC (unburnt hydrocarbons) reduction. A DPF as noted in the literature review can reduce PM (particulate matter) by up to 90% (EPA, 2010).

In the UK rail sector, SCR is only incorporated into newer diesel trains (Class 195, Class 196, Class 800) train types or recent electric train conversion to bi-mode diesel-electric (Class 769), to reduce NO_x exhaust emissions as seen with the (Grennan-Heaven and Gibbs, 2020e; FocusTransport, 2020). Work by Su et al. on

similar sized HGV (Heavy Goods Vehicles) engines to that seen in rail, diesel engines fitted with SCR can reduce the average NO_x concentration to 127 ppm, with a reduction of 65% compared to a HGV without SCR (Su et al., 2021). This is in contrast to the 1980's manufactured engines of this study which have NO_x concentrations at a maximum of 1600 ppm, as seen later in sub-section 4.2.4. The UK rail engine emissions standards, of Stage IIIB are designed for compliance for NO_x, and hence the prominent feature of SCR in new UK diesel train engines (EU, 2004). However, the lack of a PN limit value within the UK Stage IIIB rail engine standards and a PM limit of 0.025 g kWh^{-1} has meant that new rail engines are not required to incorporate DPF technology, since the Stage IIIB diesel engines designated for rail are already compliant (EU, 2004).

Table 4.1 DMUs for engine exhaust emission measurement (Angel, 2017b)

Train	Engine	Engine manufacture date	Engine after-treatment	Power (kW)
150142	Cummins NTA855R5	1986-87	No	213
153378	Cummins NTA855R5	1987-88	No	213
158903	Cummins NTA855R1	1989-92	No	260

In this study, an unconventional method was utilised to measure the engine exhaust emissions of a DMU, involving using a PEMS system for static exhaust emission measurements. Typically, in the UK rail sector, either a dynamometer or a load bank is connected to a test cell for rail engine exhaust emission testing. This involves removing the engine from the train structure and testing the emissions from the engine as a standalone unit. Exhaust measurements in this study were conducted without load. Notable PEMS testing within the rail sector includes work by the RSSB (Rail Safety and Standards Board) in 2006 testing the Cummins NTA855 engines of the 15X DMUs and more recent work by DB Cargo in 2021 on EMD 12-710G3B-EC engines of the Class 66 & 67 freight train types (I., 2006a; DBCargo, 2021). Outside of the UK, PEMS testing has been deployed in both the US and the Czech Republic, on in-service train vehicles for rail exhaust emission testing, with research by Graver and Frey in the US and. Vojtisek-Lom et al. in the Czech Republic (Graver and Frey, 2013a; Graver and Frey, 2015; Vojtisek-Lom et al.,

2020). The focus of this study, however, is to determine the static emissions inside a railway depot in line with research question 1, and is directly relevant this project.

By using PEMS in this way, this allows for the direct measurement of the gaseous species of CO, CO_2, NO, NO_2 in the DMU exhaust stream as well as to also measure the particle number and volumetric flow rate (m^3 min^{-1}) within indoor depot conditions. However, due to the lack of access to an engine dynamometer in this study, it is not possible to apply load to the engines of the DMUs and so, it is not possible to accurately determine emission factors per notch (e.g. in g kWh^{-1}), due to a lack of coupled engine dynamometer. As a consequence, the PEMS emission data in this chapter are presented in terms of wet concentrations (ppm or vol%), and mass flow rates (g s^{-1}) for the gaseous species and p cm^{-3} and p s^{-1} for particles. This is a 1 Hz measurement. The concentration and volumetric exhaust flow rate readings were unstable during the acceleration phase of testing, so the deceleration phase values have been used where possible to calculate the average notch concentrations and average notch volumetric exhaust flow rate.

Another difference in this study for the rail engine exhaust testing, is in the testing procedure, where conventionally the ISO 8178:4:2007:F standard, shown in Table 4.2 is used for vehicle engines manufactured before 2015.

Table 4.2 ISO 8178-4:2007 test cycle F for rail traction (BS, 2007b)

Mode number	**1**	**2**	**3**
Speed (rpm)	Rated speed	Intermediate speed	Low-idle speed
Torque (%max)	100	50	0
Weighting factor	0.25	0.15	0.6

For vehicle engines manufactured after 2015, the ISO 8178:4:2017:C1 standard, shown in Table 4.3 is used (Grennan-Heaven and Gibbs, 2020b; BS, 2007a; BS, 2007b). These rail standards apply for both DMUs and locomotives.

Table 4.3 ISO 8178-4:2017 test cycle C1 for rail traction (BS, 2007a)

Mode number	**1**				**2**			**3**
Speed	Rated speed				Intermediate speed			Low-idle speed
Torque (%max)	100	75	50	10	100	75	50	0
Weighting factor	0.15	0.15	0.15	0.1	0.1	0.1	0.1	0.15

In this study, in order, to determine the engine emissions at all 8 notch power settings (notch 0 → 7), a much shorter testing interval of approximately 1 minute per notch was used with some extra time allocated for idle due to engine warm-up requirements. Due to the indoor environment of the tests of this study, it was not possible to conduct 15 min continuous engine exhaust measurements on the designated notches of the ISO 8178-4 (F) standard, due to health & safety concerns raised by rail staff of the significant large quantities of diesel fumes in a confined, indoor environment (Northern Rail Depot Staff - Neville Hill, 2018). As outlined in detail earlier in this chapter, the DMUs were tested on a much shorter interval time.

For CO and CO_2, the PEMS system recorded the wet concentrations in %vol, with the gases of NO, NO_2 and NO_x recorded in ppm and the species of THC was recorded in units of ppmC. An AFR (Air/Fuel ratio) was estimated for each notch, using the Brettscheider Spindt method, with further details on this method provided in the methodology chapter (Chapter 3) (Silvis, 1997). To summarise this method briefly, this involved utilising the species averaged concentration at each notch within a Carbon balance, to determine the AFR for that notch as seen in Equation 4.1. The estimated AFR values for each of the DMUs for all of the available notch settings are provided in Table 4.4.

$$\text{AFR} = \frac{n_{O_2}\,(M_{w(O_2)}+3.773(M_{w(N_2)})}{12aC+1.9bH+cO} \quad (4.1)$$

where n is the moles of Oxygen, $M_{w(O_2)}$ is the molecular weight of Oxygen = 32, $M_{w(N_2)}$ is the molecular weight of Nitrogen = 28, aC is the number of atoms of Carbon = 1, bH is the number of atoms of Hydrogen = 1.9, cO is the number of atoms of Oxygen = 0.03

Table 4.4 Average exhaust temperature and AFR per notch for the 3 DMUs tested

	150142	**153378**	**158903**	**AFR 150**	**AFR 153**	**AFR 158**
	T_e (°C)	**T_e (°C)**	**T_e (°C)**			
Notch 0	184	240	228	136	165	95
Notch 1	203	237	260	82	84	44
Notch 2	221	260	281	68	63	42
Notch 3	253	263	317	45	46	34
Notch 4	267	301	336	41	41	32

	150142	153378	158903	AFR 150	AFR 153	AFR 158
	T_e (°C)	T_e (°C)	T_e (°C)			
Notch 5	273	306	343	38	38	32
Notch 6	270	307	335	38	37	32
Notch 7	267	293	321	36	35	31

A series of plots for each species was plotted against time to identify any outliers and instability in the data for each of the 3 DMUs tested. The CO and CO_2 data were relatively stable across all power settings. Fluctuations in the emission data for PN and the NO_x gases, were averaged for the most stable regions at each notch setting via visual inspection and then averaging for this stable region to give a representative value for this notch setting. This procedure was repeated for each of the 3 DMUs to correct for fluctuations in the data. Through this process, outlier concentration values and PN values were removed from the data sets for the 3 DMUs to remove spikes in the data which did not correspond to the notch power settings of the testing procedure of this study. The averaged values were then plotted for each species against notch power setting as illustrated in sections 4.22-4.27, in line with research question 1, in determining the engine emission levels of Northern Rail DMUs in a railway depot.

Possible reasons for this reduction in temperature could be attributed to instability of the engine and transient test conditions. Typically, the DMU engines are not tested on such high-idle conditions (i.e. notches 6 and 7), without applied load, for greater than 10 s within the depot, and so testing at 1 min per notch on average may have induced instability in the engine at the higher notch positions of notches 5-7. Figure 4.1 illustrates this behaviour, with the exhaust temperature continuing to increase for the 150 DMU during the deceleration phase, stepping down from notch 7 down to notch 5. Another potential reason, for the continued exhaust temperature increase during deceleration, is the short transition between acceleration and deceleration, of 1 min, which may not allow the engine enough time to cool down, when stepping from the maximum notch setting, of notch 7, down to notch 6 and then further down on to the lower notch positions of notches 0-5. Similar trends are observed with the 153 DMU (Figure 4.2) and the 158 DMU (Figure 4.3), as noted earlier with reductions in exhaust temperature at the higher notch positions of notches 6 and 7, the same reasons can be attributed for this reduction.

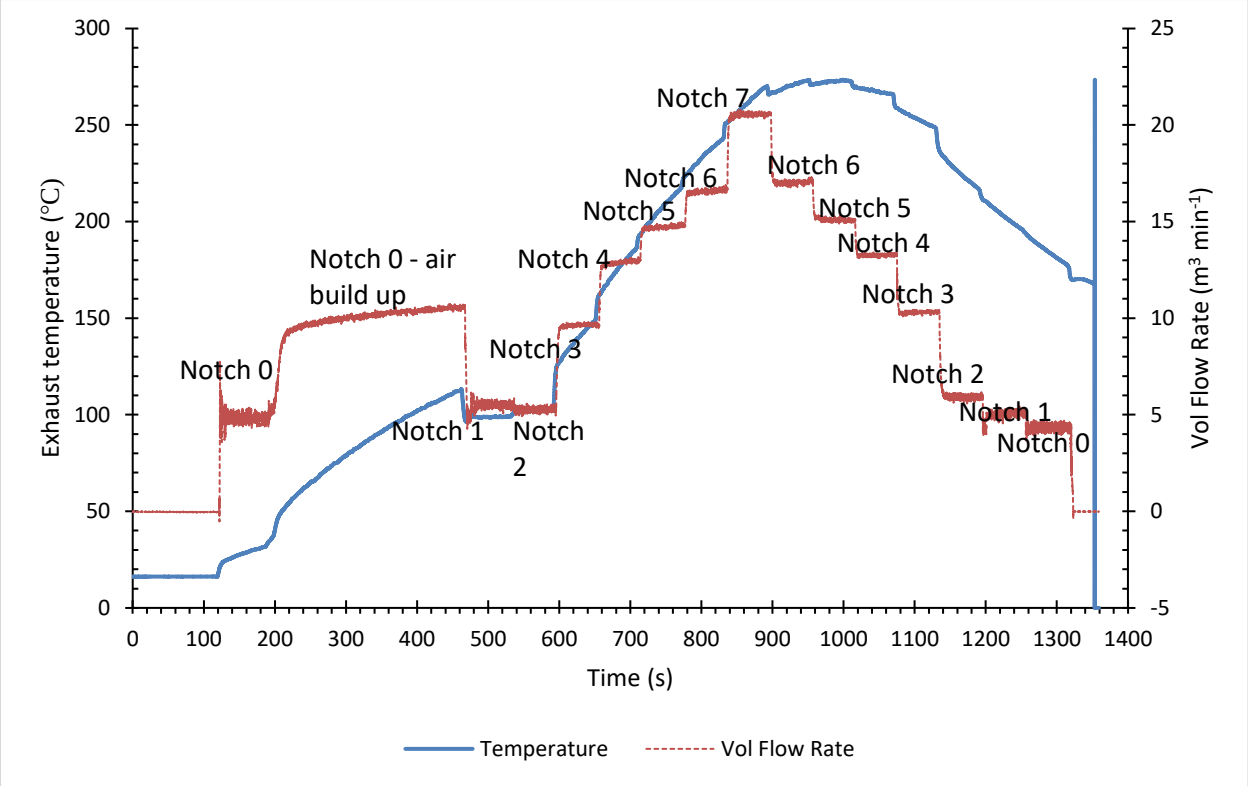


Figure 4.1 Change in exhaust temperature with notch position for the 150 DMU.

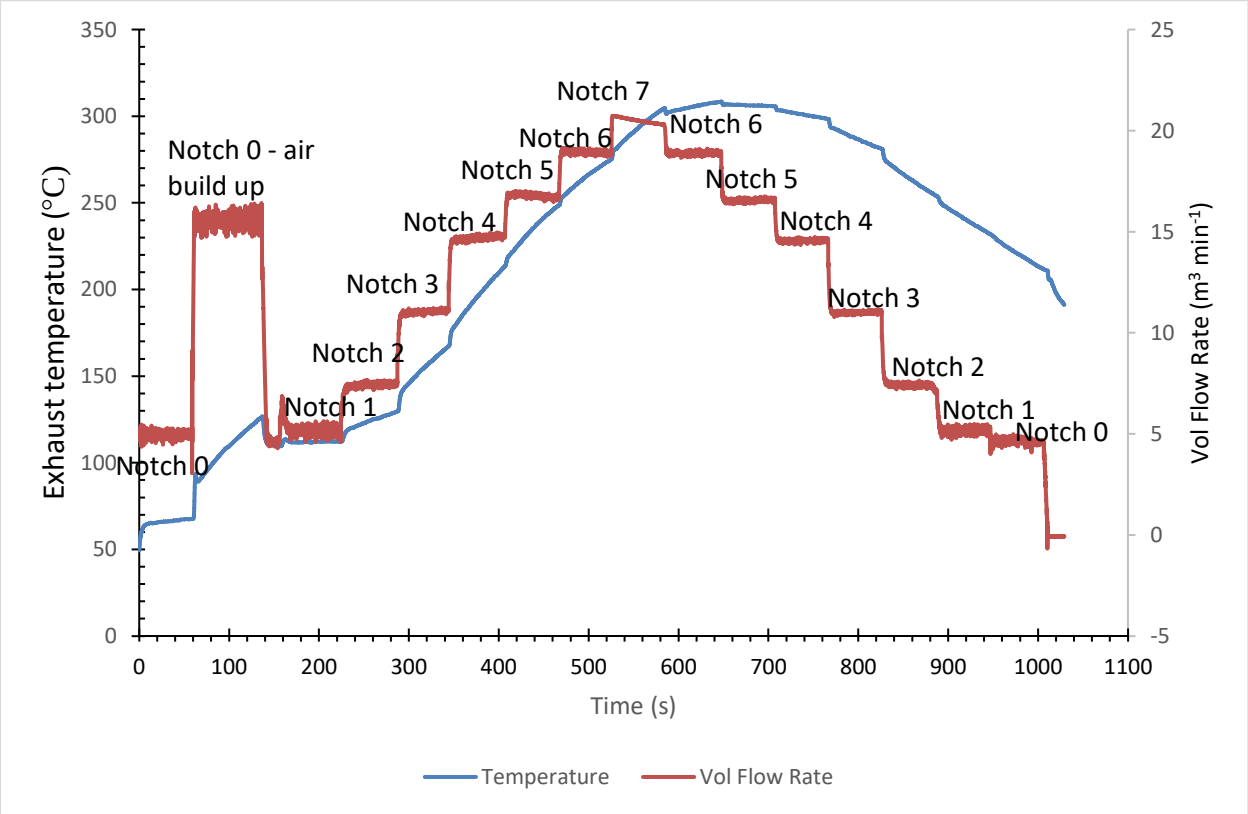


Figure 4.2 Change in exhaust temperature with notch position for the 153 DMU.

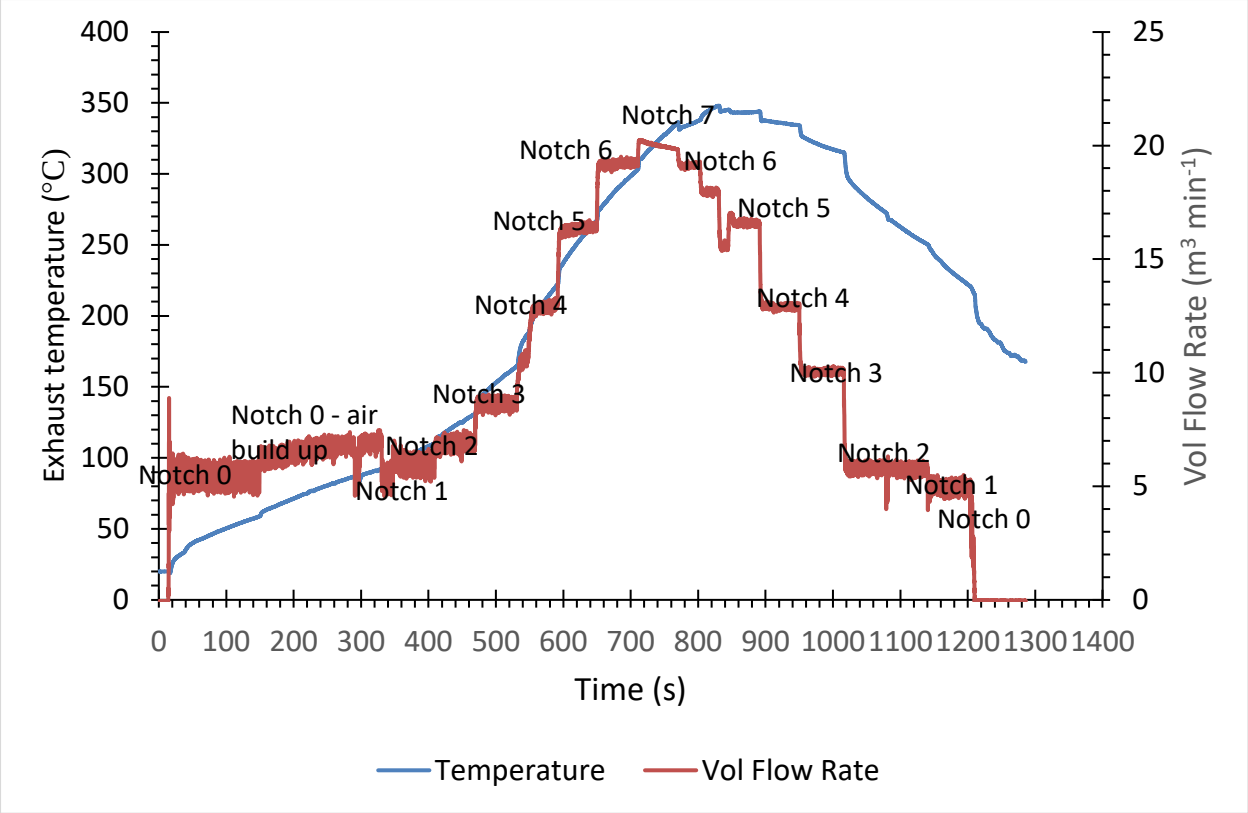


Figure 4.3 Change in exhaust temperature with notch position for the 158 DMU.

4.2.2 CO emissions in ppm

There is a proportional relationship between the concentration of CO and the engine power setting as seen in Figure 4.4. The increasing CO concentration can be attributed to a reduction in the AFR ratio with increasing notch. Between notches 5 and 7, the AFR for the 150 and 158 DMUs were almost constant with a reduction of 38 → 36 for the 150 DMU and 32 → 31 DMU for the 158 DMU. CO emission data was unavailable for the 153 DMU due to erroneous data.

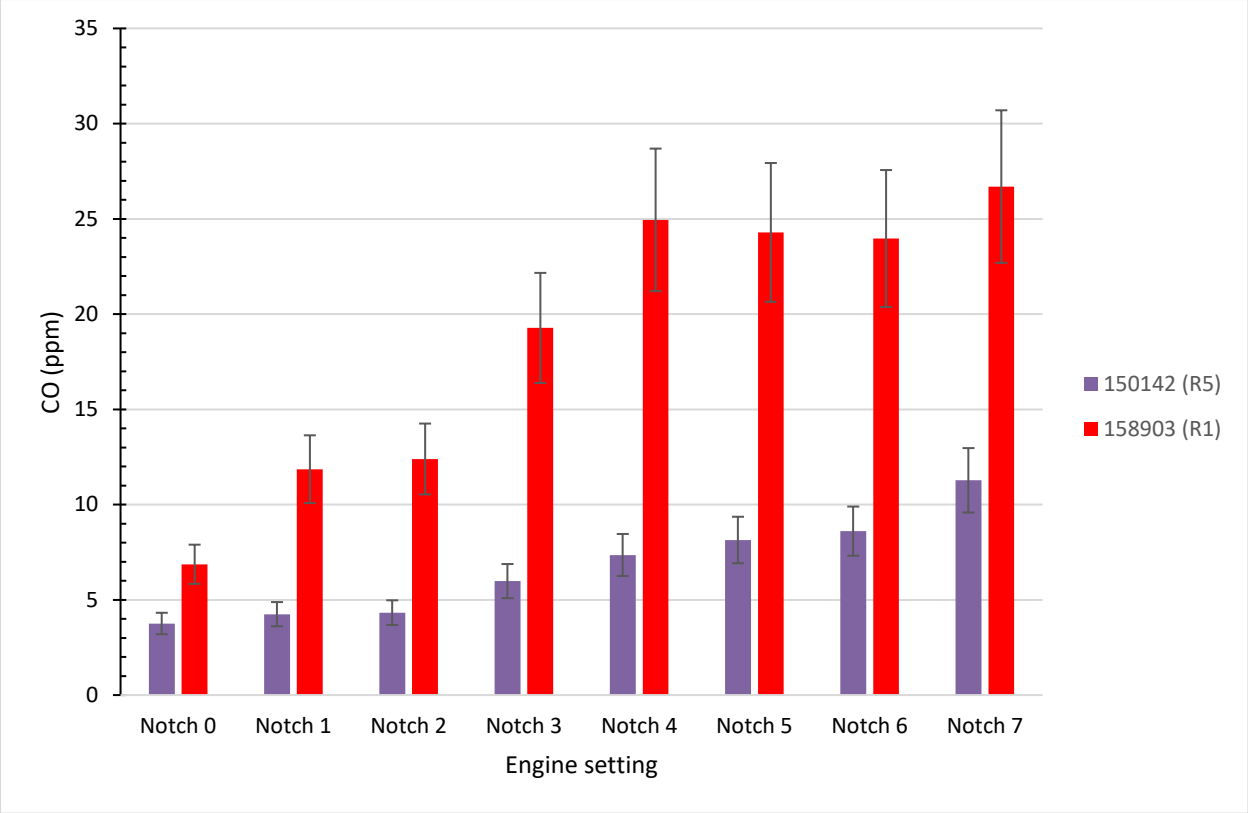


Figure 4.4 CO data for different DMUs tested in the Neville Hill railway depot

4.2.3 NO exhaust concentration data

For NO, the relationship is also proportional between NO and exhaust temperatures, i.e. high concentrations of NO were observed at the high powered notch settings as seen in Figure 4.5. The highest notch averaged concentration of NO was seen at notch 7 with over 1500 ppm from the 153 DMU as noted in Figure 4.5.

At the lowest notch of notch 0, the amount of NO produced is low since the engine temperature is also low, at 184°C on idle with the 150 DMU, 240°C for the 153 DMU and 228°C, as seen in Table 4.4. As the notch position increased from notch 0 to the maximum notch setting of notch 7, in most instances, the exhaust temperature increased for every notch with the AFR conversely decreasing from notch 0 to notch 4; creating the conditions for greater NO generation under a richer AF(air-fuel) mix. For the 158 DMU, the rise and fall in exhaust temperature after notch 4, can explain the reduction in NO concentration at notch 6. The 153 and 158 DMUs, continued the trend of the lower notches, with an increase in notch resulting in an increase in NO concentration, as seen at the lower notch settings, with a reduction in AFR with increasing notch. Although there is a very minor reduction in

exhaust temperature for the 153 DMU, the change in temperature was too small, to impact the NO concentration between notches 5-7.

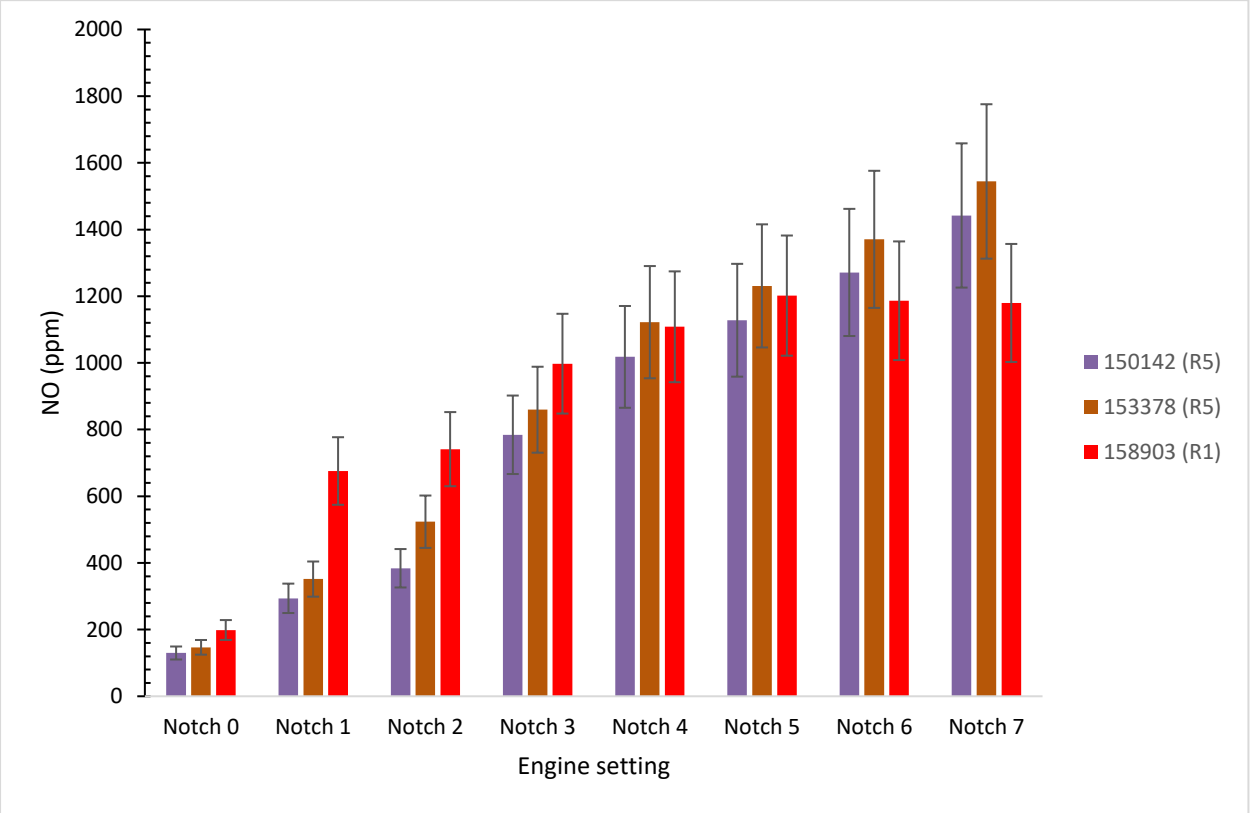


Figure 4.5 NO data for different DMUs tested in the Neville Hill railway depot

Comparing this data against literature data from Graver et al., as seen in Table 4.5, shows that the DMU NO concentrations at idle below that of EMD F59HI diesel-electric train of the Graver et al. study (Graver et al., n.d). This is expected as the DMUs in this study were tested without load, which will lower the amount of NO generated from the engine exhaust. However, at full notch, the trend is different with higher NO concentrations seen within the DMUs, in particular the 150 and 153 DMUs, when compared against the EMD 59HI. At full notch, the EMD 59HI had a much lower NO concentration than the DMUs. Possible reasons for include difference in engine type, the EMD 59HI is a diesel-electric train powered by a locomotive rated at 2280 kW contrast to the DMUs which have individual engines rated at 298-350kW. In addition the trains were tested using two completely different test procedures, the EMD 59HI was tested during train movement between 2 points over 173 mi (i.e. over-the-rail) by Graver et al. whereas the DMUs were tested in a static position without applied load .

Table 4.5 Comparison of NO concentration data with EMD 59HI data from Graver et al. (Graver et al., n.d)

Engine	NO (ppm) at Notch 0	NO (ppm) at Full notch
150 DMU	130	1442
153 DMU	147	1554
158 DMU	199	1180
EMD F59HI	302	1160

4.2.4 NO_x exhaust concentration data

For NO_x, the relationship between exhaust concentration and notch power setting is also on average proportional, barring some minor exceptions with the 158 DMU, with high concentrations of NO_x observed at the high notch settings of notch 6 and 7 as seen in Figure 4.6. The highest notch averaged concentration of NO_x was seen at notch 7 with almost 1600 ppm from the 153 DMU as seen in Figure 4.6. The higher NO_x emissions at higher notches can be attributed to the higher exhaust temperature , consistent with trends in literature in which NO_x increases with exhaust temperature (Semakula and Inambao, 2018; Zevenhoven and Kilpinen, 2002). Engine instability could be attributed to the reduction in NO_x concentration from notch 5 to notch 7, for the 158 DMU.

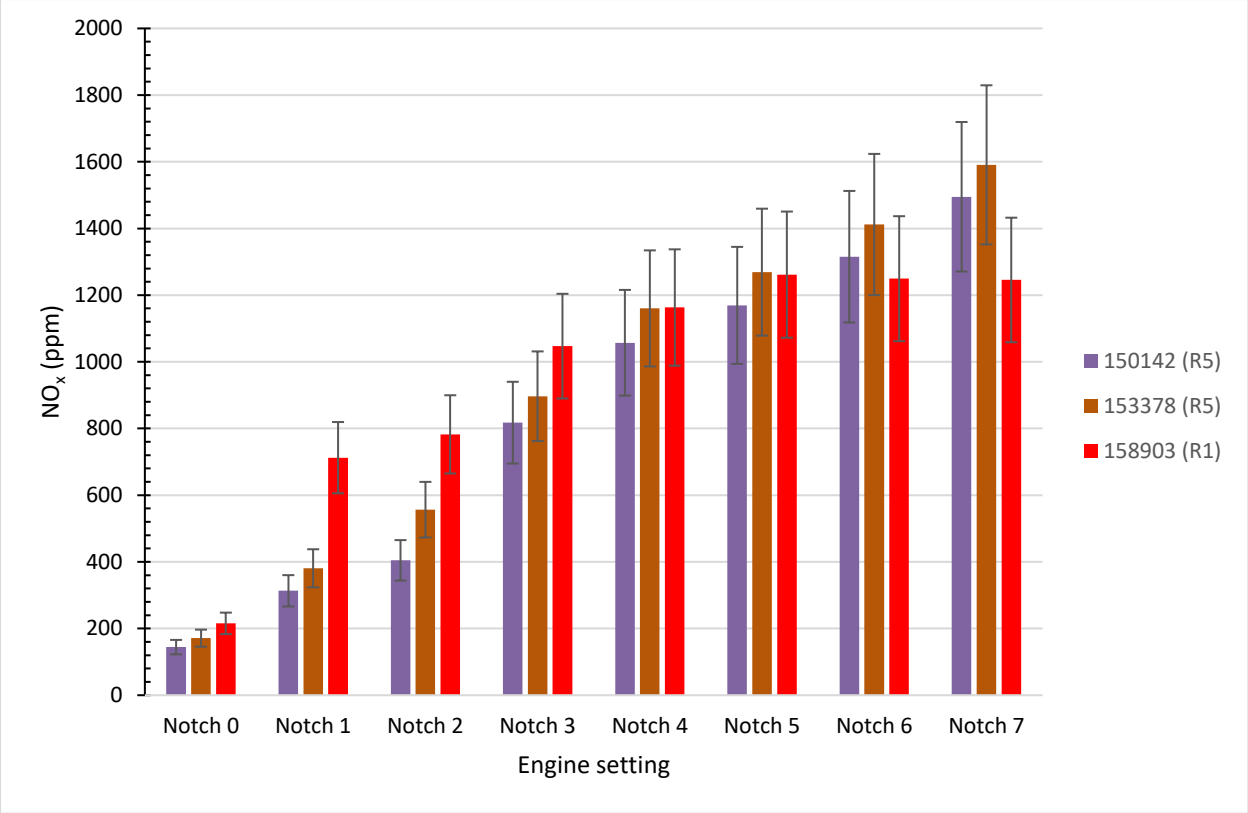


Figure 4.6 NO_x data for different DMUs tested in the Neville Hill railway depot

4.2.5 NO_2 exhaust concentration data

The NO_2 concentrations, generally increased with increasing notch power setting across the 3 DMUs as seen in Figure 4.7, similar to the NO and NO_x exhaust concentrations discussed previously. The minor drop in NO_2 concentration for the 158 DMU can be attributed to engine instability. More broadly however across the DMUs, the increases in NO_2 concentration with notch power setting can be attributed to a decreasing AFR, with a peak of 79-126 at idle across the 3 DMUs and a relatively low exhaust temperature of 183-228°C on idle. The 158 DMU demonstrated the highest NO_2 concentrations across the majority of the notch power settings, excluding the idle power mode, and this can be explained its' much leaner AFR (31-32) and higher exhaust temperatures (321-343°C), in contrast to the other 2 DMUs, 150 and 153.

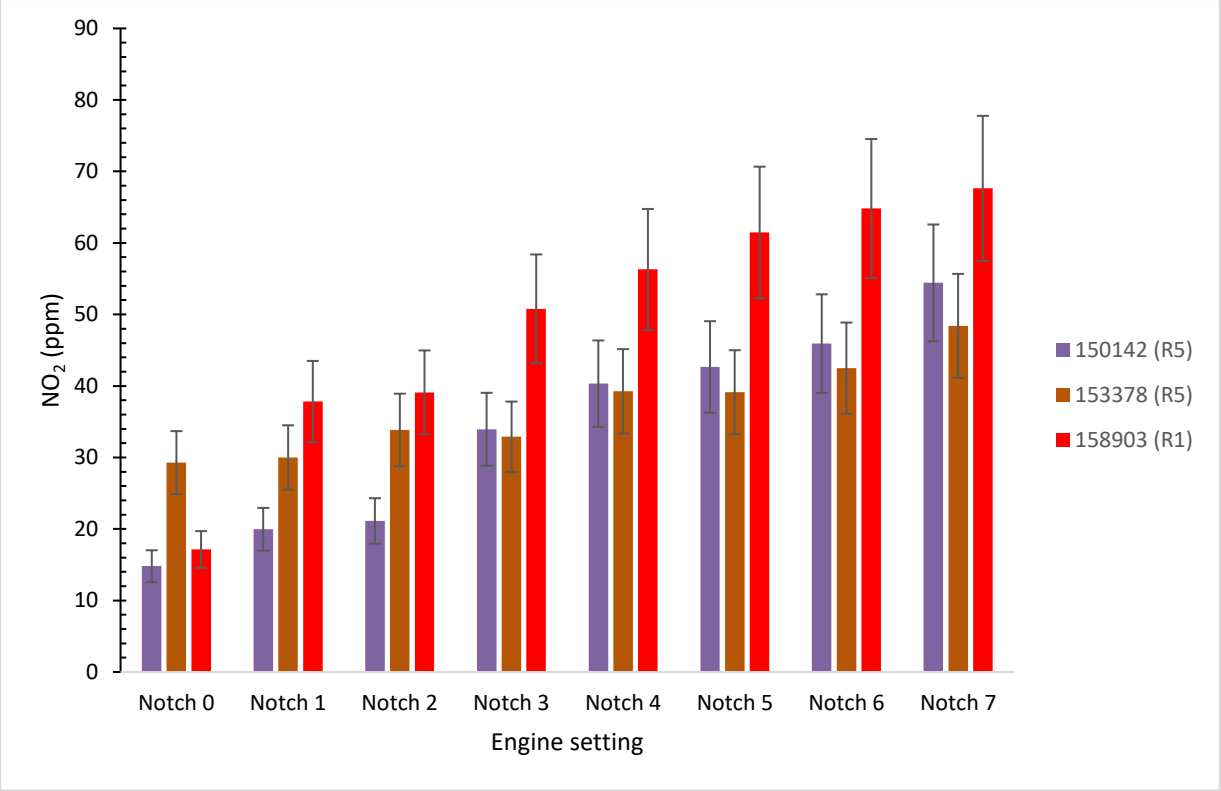


Figure 4.7 NO_2 data for different DMUs tested in the Neville Hill railway depot

Figure 4.8 shows the primary NO_2, determined by taking the ratio of exhaust NO_2: NO_x. At idle, the 153 DMU has the highest primary NO_2, consistent with the exhaust NO_2. However, as the notch setting increased the primary NO_2 decreased indicating a greater fraction of NO in the exhaust NO.

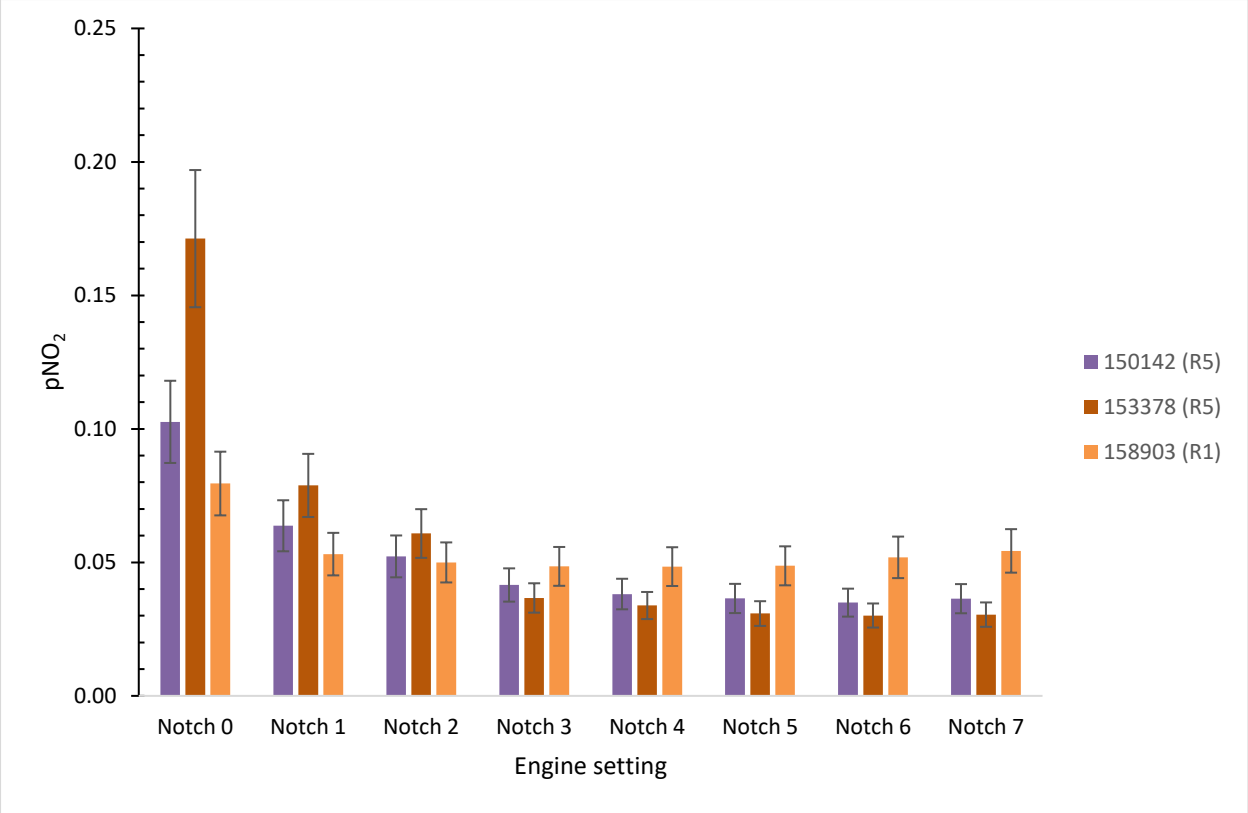


Figure 4.8 Exhaust primary NO_2 calculated from the DMUs in the Neville Hill railway depot

4.2.6 Total hydrocarbons (THC) exhaust concentration data

The THC concentration showed variable behaviour with increasing notch setting as seen in Figure 4.9. This can be attributed to two combating factors here: when notches stepped up, combustion temperatures increases which will reduce THC but at the same time, AFR reduces which will increase THC emissions. Incomplete combustion within diesel engines can arise due to numerous factors including “untidy injection, excessive nozzle cavity bounce and injector needle bounce” as noted by Payri et al, consequently increasing the amount of unburnt hydrocarbons in the exhaust (Payri et al., 2009). The broad increase in THC concentration for the 158 DMU after notch 1, with increasing notches can be attributed to the fact that the AFR has been reduced or air-fuel mixtures were getting richer. For the 150 and 153 DMUs, the initial decrease in THC concentration from idle, following by a fluctuation in THC concentration between notches 1 to 4, after which the THC concentration increases from notches 5 to 7 could be attributed to engine stability.

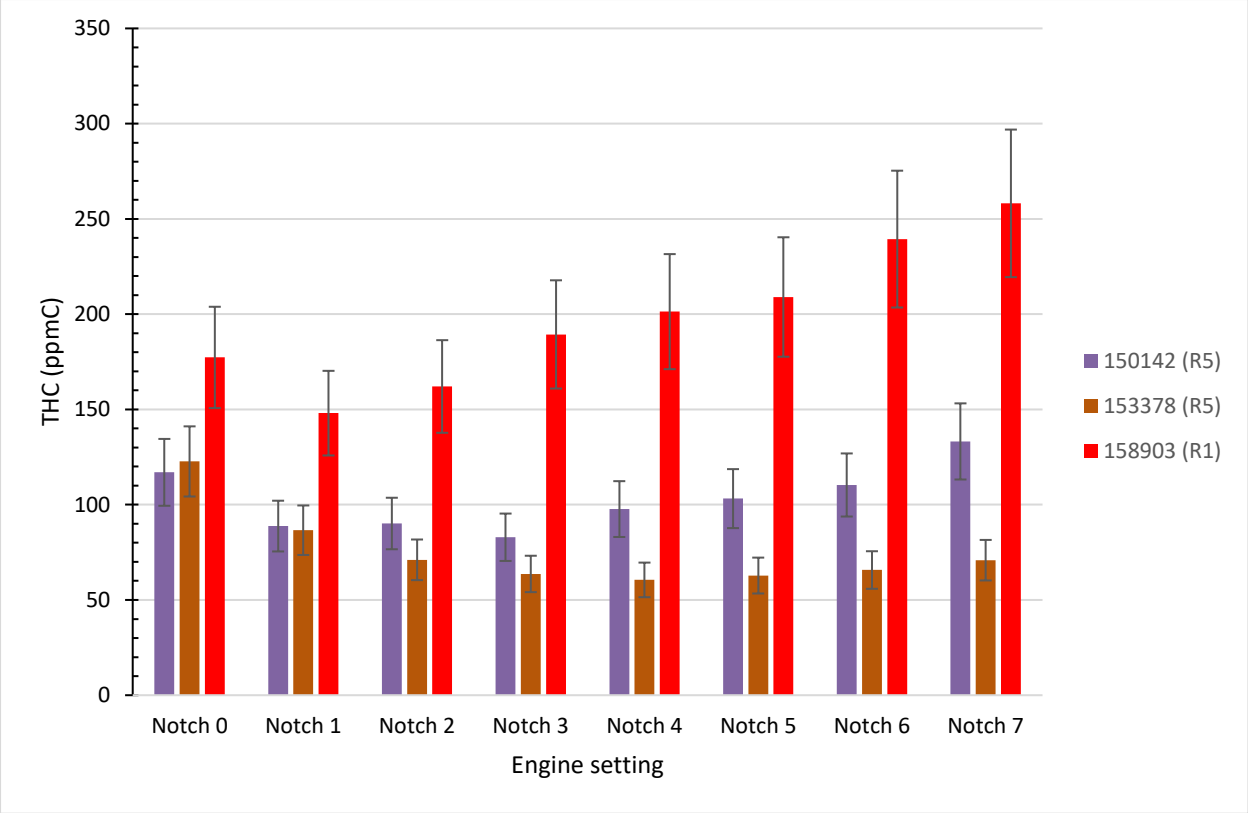


Figure 4.9 THC data for different DMUs tested in the Neville Hill railway depot

4.2.7 Particle Number (PN) exhaust concentration data

The total number concentrations for PN, similar to NO_x and THC, generally increased with increasing notch for the 150 and 158 DMUs, between notches 1-5 as seen in Figure 4.10. At notches 6 and 7, the lean AFR can be attributed to the reduction in PN (Grennan-Heaven and Gibbs, 2020c). For PN, high total number concentrations of $1.7x10^5$ cm^{-3} were observed for the 150 DMU, as seen in Figure 4.10. At the higher notches, of notch 6 and 7, the 15X DMUs had PN concentrations below $2x10^6$ cm^{-3} at notch 6. The major reduction in PN at notch 5 for 153 DMU can be attributed to engine instability.

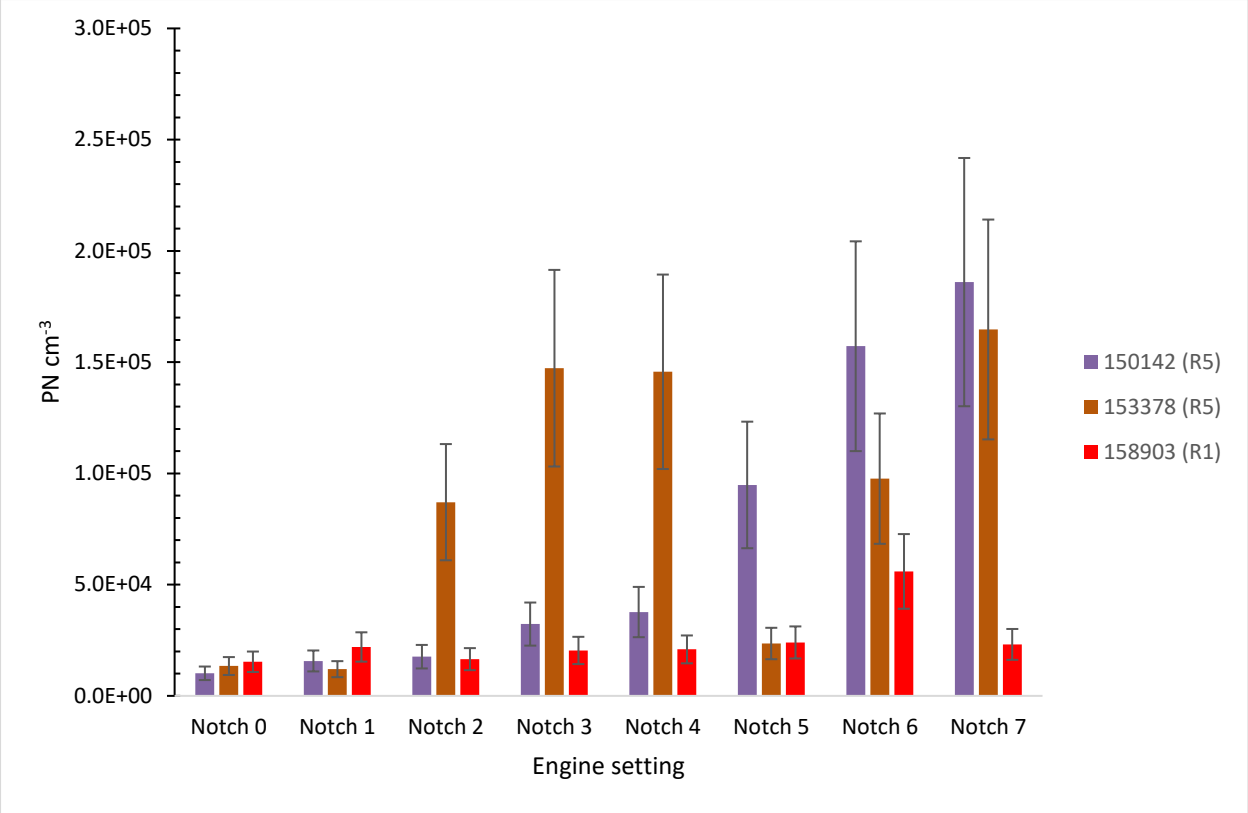


Figure 4.10 Particle Number (PN) data for different DMUs tested in the Neville Hill railway depot

4.2.8 Comparison of the emission indexes between DMUs from this study and literature data

The emission index is a standard unit of measure for comparing emissions from different engines on a like-for-like basis. The exhaust concentrations from the DMUs, as outlined in the previous sub-sections 4.2.2-4.26, can be converted into an emission index (EI), using Equations 4.2 and 4.3:

$$EI_x\ (g\ kg^{-1}) = 1000\ K\ [X](in\ ppm)\ (1+AFR)\ x\ 1x10^{-6} \quad (4.2)$$

where EI_x is the emission index of pollutant x, K is the ratio of the molecular weight of species x divided by the molecular weight of air, [X](in ppm) is the concentration of a given pollutant X in ppm

$$EI_x\ (g\ kg^{-1}) = 1000\ K\ [X](in\ vol\%)\ (1+AFR)\ x\ 1x10^{-2} \quad (4.3)$$

where EI_x is the emission index, K is the ratio of the molecular weight of species X divided by the molecular weight of air, [X](in vol%) is the exhaust concentration of a given pollutant X in %vol

The emission indexes determined for the 150 (Table 4.6), 153 (Table 4.7), 158 (Table 4.8) DMUs, can be compared against literature data from similar sized engines, to see how this study's data compares against these. The emission index values show variations across the different notch power settings. For CO_2, the highest emission index is noted at notch 4 for the 3 DMUs with a gradual increase from notch 0 to a peak at notch 4, followed by a subsequent decrease from notches 4 to 7. Different trends are observed however for CO, THC and NO_x with notch 0 corresponding to the highest emission index for CO and THC. For NO_x, the emission index increases with notch, with the highest NO_x emission index noted at the notch 7, the highest notch power setting.

Table 4.6 Emission index for the 150 DMU

	CO (g kg^{-1})	**CO_2 (g kg^{-1})**	**THC (g kg^{-1})**	**NO_x (g kg^{-1})**
Diesel - 150 Notch 0	0.5	3051.0	8.8	31.4
Diesel - 150 Notch 1	0.3	3104.6	4.1	41.2
Diesel - 150 Notch 2	0.3	3127.8	3.4	44.1
Diesel - 150 Notch 3	0.3	3195.8	2.1	59.6
Diesel - 150 Notch 4	0.3	3216.9	2.2	69.8
Diesel - 150 Notch 5	0.3	3143.5	2.2	72.9
Diesel - 150 Notch 6	0.3	3147.0	2.4	80.9
Diesel - 150 Notch 7	0.4	3154.3	2.8	88.8

Table 4.7 Emission index for the 153 DMU

	CO (g kg^{-1})	**CO_2 (g kg^{-1})**	**THC (g kg^{-1})**	**NO_x (g kg^{-1})**
Diesel - 153 Notch 0	0.0	3035.1	11.3	45.1
Diesel - 153 Notch 1	0.0	3102.5	4.1	51.6
Diesel - 153 Notch 2	0.0	3140.9	2.5	56.5
Diesel - 153 Notch 3	0.0	3195.3	1.6	66.4
Diesel - 153 Notch 4	0.0	3219.1	1.4	77.2
Diesel - 153 Notch 5	0.0	3146.9	1.4	79.3
Diesel - 153 Notch 6	0.0	3154.0	1.4	85.7
Diesel - 153 Notch 7	0.0	3165.8	1.4	91.9

Table 4.8 Emission index for the 158 DMU

	CO (g kg^{-1})	CO_2 (g kg^{-1})	THC (g kg^{-1})	NO_x (g kg^{-1})
Diesel - 158 Notch 0	0.6	3073.9	9.4	33.0
Diesel - 158 Notch 1	0.5	3194.0	3.7	50.8
Diesel - 158 Notch 2	0.5	3203.2	3.8	53.2
Diesel - 158 Notch 3	0.6	3255.3	3.6	57.4
Diesel - 158 Notch 4	0.8	3264.9	3.7	61.6
Diesel - 158 Notch 5	0.8	3179.6	3.8	65.5
Diesel - 158 Notch 6	0.8	3176.5	4.3	65.2
Diesel - 158 Notch 7	0.8	3179.0	4.6	64.1

Zarling et al. determined emission indexes for a HGV Caterpillar C12 312kW engine for the species of HC, CO and NO_x in g kg^{-1} with the engine specifications provided in Table 4.9 (Zarling et al., 2002). For a consistent comparison, only the idle data from Zarling et al. was utilised, as seen in Table 4.10.

Table 4.9 Engine specifications for Caterpillar C12 HGV engine (Zarling et al., 2002)

Engine	Modified Caterpillar C12 engine compliant to 1998 post-consent decree emission levels
Model year (MY)	1998
Number of cylinders	6
Volume	12 litre
Turbocharged	Yes
Aftercooled	Yes
Rated maximum power	312 kW @ 2100 rev/min
Peak torque	2237 Nm @ 1200 rev/min
Idle speed	800 rev/min

Table 4.10 HGV Caterpillar C12 emission index data at idle power

	CO (g kg^{-1})	THC (g kg^{-1})	NO_x (g kg^{-1})
HGV Caterpillar C12	31.07	5.64	59.97
150 DMU	0.5	8.8	31.4
153 DMU	0	11.3	45.1
158 DMU	0.6	9.4	33.0

The emission index data from Table 4.10 shows that the CO and NO_x emission indexes from the Caterpillar C12 engine are higher than the DMUs tested in this study, in the case of CO, significantly higher than the DMUs. The difference is engine load is a major difference between the two engines tests. The DMUs tested at idle without load would lead to a higher AFR and lower CO in contrast to the Caterpillar C12 engine. The very low exhaust concentrations of CO observed in the DMUs, indicate better combustion of the carbon components in the fuel, into CO_2, in contrast to the Caterpillar C12 engine. However, the THC emission index for the Caterpillar C12 is lower than DMUs of this study, creating an unusual scenario, where on the one hand, less unburnt hydrocarbons are observed in the Caterpillar C12, indicating more efficient combustion than the DMUs, but on the other hand, very high quantities of CO noted from the Caterpillar C12, indicates very inefficient combustion. In terms of NO_x, the Caterpillar C12 engine has a greater NO_x emission index than the DMUs, as seen in Table 4.10.

. One reason for this could be the difference in testing resting, with the Caterpillar C12 tested with load, as per the ISO 8178-C1 procedure, in contrast to this study, which tested the DMUs without load, using a much shorter test period on idle. It is expected that measuring the exhaust emissions with applied load, as was the case with the Caterpillar C12 engine, is likely to result in higher NO_x exhaust emissions, than an engine tested without load, as is the case for the DMUs in this study. A lack of data on the AFR and exhaust temperature from the Caterpillar C12 make it difficult to determine categorically if these variables contributed to the high NO_x emission limit. It is possible that the higher maximum rating of the Caterpillar C12 engine at 312 kW than the DMUs, as seen in Table 4.11, could be another factor attributed to the higher NO_x emission index, however, further engine specifications, such as AFR and exhaust temperature, would be needed to investigate this further, which is beyond the work of this study.

Table 4.11 Specifications of rail DMUs of this study and the Caterpillar C12 HGV engine used for comparison of exhaust mass flow rates (Porterbrook, 2017b; Porterbrook, 2017c; Porterbrook, 2017f; Zarling et al., 2002)

Engine	Sector	Class	Engine Manufacture date	Engine Power (kW)	rpm	# of strokes	Turbocharged
Cummins NTA855R5	Rail	150	1985-86	213	2100	4	No
Cummins NTA855R5	Rail	153	1987-88	213	2100	4	No
Cummins NTA855R1	Rail	158	1987-89	260	2100	4	No
Modified Caterpillar C12	HGV Road	-	1998	312	800	4	Yes

4.2.9 Comparison of exhaust emission data of this study against 170 exhaust emission data on a concentration basis

Using external data obtained from the RSSB, a comparison was conducted between the RSSB's 170 DMU (Table 4.12), to support research question 1, to compare the emissions of this study with other rail vehicle data (Gibbs et al., 2020). The RSSB's test involved using a load bank with the exhaust emission data for the 170 DMU provided in Table 4.13 (Gibbs et al., 2020). When comparing the PEMS data of this study against the 170 engine emission data, the NO_x concentration at idle is higher at 250 ppm than that measured by the 15X DMUs measured using the Horiba OBS-One PEMS of this study which ranged between 110 and 215 ppm.

Table 4.12 Specification of the 170 train tested by the RSSB for exhaust emissions via a load bank (Gibbs et al., 2020)

Train	Engine	Engine Manufacture date	Engine after-treatment	Power (kW)	PEMS system
170	MTU 6R183TD13H	1999-2005	No	315	AVL415

Table 4.13 Average emission concentrations obtained from external data for a 170 train exhaust using a load bank.

170 (MTU)	CO	CO_2	NO	NO_x	NO_2	THC	PN
	%vol	%vol	ppm	ppm	ppm	ppm	# cm^{-3}
Notch 0	-	2	-	250	-	-	-
Notch 7	-	12	-	1500	-	-	-

Varella et al as noted earlier in Chapter 3, has an inaccuracy of typically 15% for PEMS systems on light duty vehicles. Using this 15% figure, as a proxy for the uncertainty for heavy duty vehicles, the 170 still has a higher NO_x exhaust concentration at idle than the 15X DMUs of this study (Varella et al., 2018). It must be noted that both the 170 DMU and 15X DMUs have no aftertreatment systems for NO_x reduction. At full power, the 170 has a similar NO_x concentration as the 15X DMU tests at maximum notch, of this study with 1500 ppm for the 170 train on full power and 1495 ppm for the 150 DMU on maximum notch respectively, as seen in Figure 4.11.

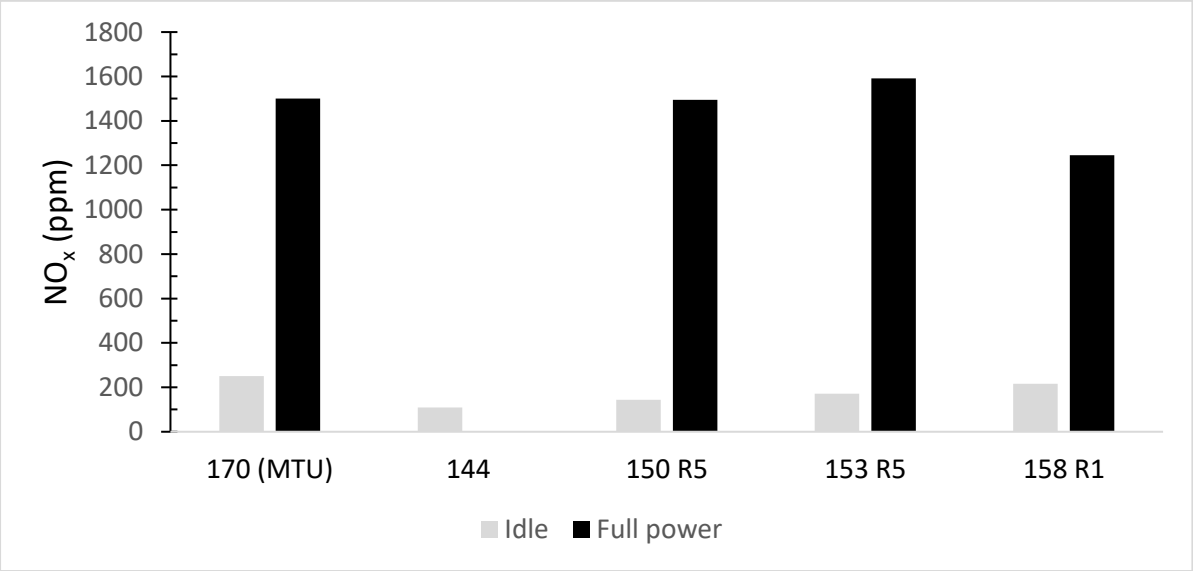


Figure 4.11 NO_x data for different DMUs tested in the Neville Hill railway depot

4.2.10 Average exhaust mass flow rates of each species for each notch setting using a PEMS system

The averaged data from the PEMS unit for each notch setting during the deceleration phase were obtained as wet concentration values in ppm and vol%. These have been converted into a mass flow rate via Equations 4.4 and 4.5.

$$M = \frac{[X]\ (in\ ppm)}{10^6} \times \rho_E \times q_E \times \frac{1000}{60} \quad (4.4)$$

where M is the mass flow rate of the exhaust for a given pollutant in g s^{-1}, [X](in ppm) is the average concentration for a given notch for a given pollutant x in ppm, ρ_E is the exhaust density in kg m^{-3}, q_E is the average exhaust volumetric rate for a given notch in m^3 min^{-1}.

$$M = \frac{[X](in\ vol\%)}{10^6} \times \rho_E \times q_E \times \frac{1000}{60} \quad (4.5)$$

where M is the mass flow rate of the exhaust for a given pollutant in g s^{-1}, [X](in vol%) is the average exhaust concentration for a given notch for a given pollutant in vol%, ρ_E is the exhaust density in kg m^{-3}, q_E is the average exhaust volumetric rate for a given notch in m^3 min^{-1}.

Assumptions

- The exhaust density was not available from the PEMS so a typical value of 1.2 kg m^{-3} has been used.

After converting the species of NO, NO_2, NO_x, CO and CO_2 to mass flow rates as per Equations 4.4 and 4.5, graphs of the flow rates of each species against the notch power setting were plotted. Due to limited data on exhaust mass flow rates in literature, in section 4.2.10 only the idle data is considered for comparison with a 1996 Cummins bus engine, and in section 4.2.11, only the idle setting (notch 0) and full power exhaust mass flow rates will be utilised for analysis in sub-section 4.2.11, when comparing the 15X DMUs of this study with 170 DMU data from the RSSB.

Data from Toback et al, was used as a comparison point for the mass exhaust flow rates from this study (Toback et al., 2004). Toback et al. conducted exhaust emission measurements on a 1996 Cummins 5.9 l B series 190 HP bus engine under ambient conditions of 18.3°C and 40 %RH (Relative Humidity), and calculated the emission mass flow rates for NO_x, CO and THC in g s^{-1} at idle. The

specifications for the Cummins bus engine are provided in Table 4.14 together with the DMUs of this study. For NO_x and CO, the DMUs of this study emission mass flow rates at idle were lower than that observed in the Cummins bus engine of the Toback et al. study as seen in Figs. 4.12-4.14. However, for THC, the 158 DMU had a higher exhaust mass flow of THC at idle than the Cummins bus engine of Toback et al. (Toback et al., 2004). It must be noted that there is difference in the engine size between the Cummins bus engine with a maximum rate powered at 142 kW from the Toback et al. research, whereas the DMUs of this study ranged between 172 – 260 kW. It is possible that the AFR ratio is much leaner for the Cummins bus engine on idle power, than the DMUs in this study, and so could be the reason for higher emission mass flow rates of NO_x and CO, however, further details of the AFR of Cummins bus engine would be required, which is currently unavailable.

Table 4.14 Specifications of rail DMUs of this study and the Cummins G-12 bus engine used for comparison of exhaust mass flow rates (Porterbrook, 2017b; Porterbrook, 2017c; Porterbrook, 2017f; Angel, 2017e; Toback et al., 2004)

Engine	Sector	Class	Engine Manufacture date	Engine Power (kW)	rpm	# of strokes	Turbocharged
Cummins NTA855R5	Rail	150	1985-86	213	2100	4	No
Cummins NTA855R5	Rail	153	1987-88	213	2100	4	No
Cummins NTA855R1	Rail	158	1987-89	260	2100	4	No
Cummins B Series	Bus	n/a	1996	142	2200	4	Yes

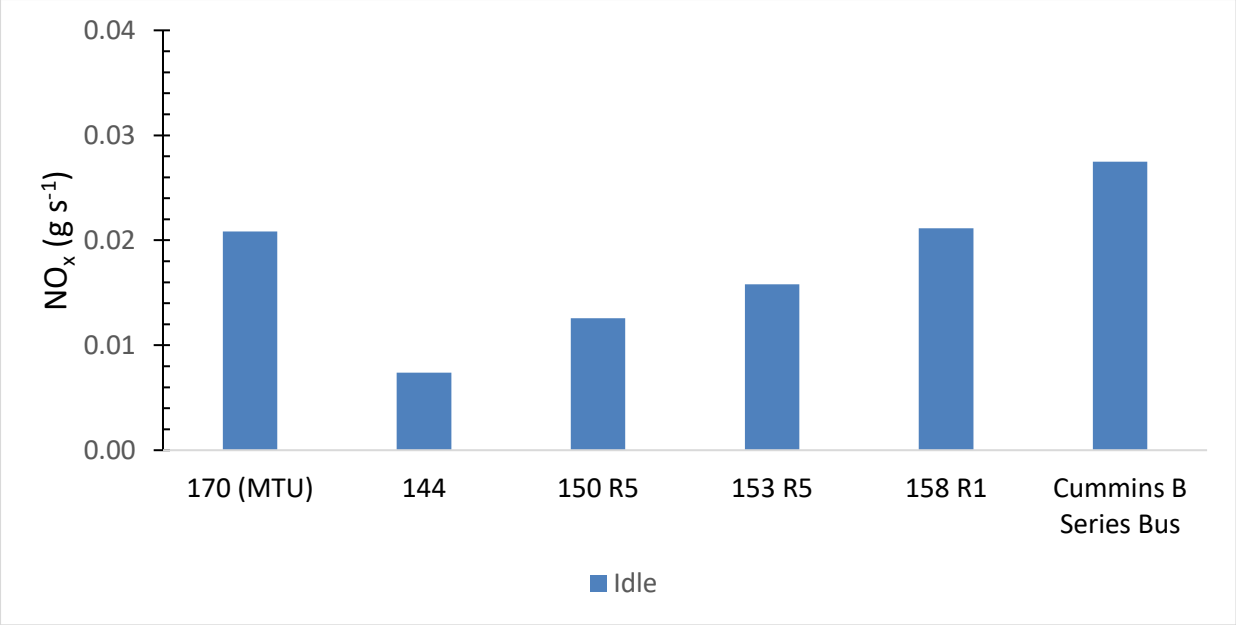


Figure 4.12 Comparison of NO_x mass flow rate of the DMUs of this study with Cummins bus engine emissions from literature (Toback et al., 2004)

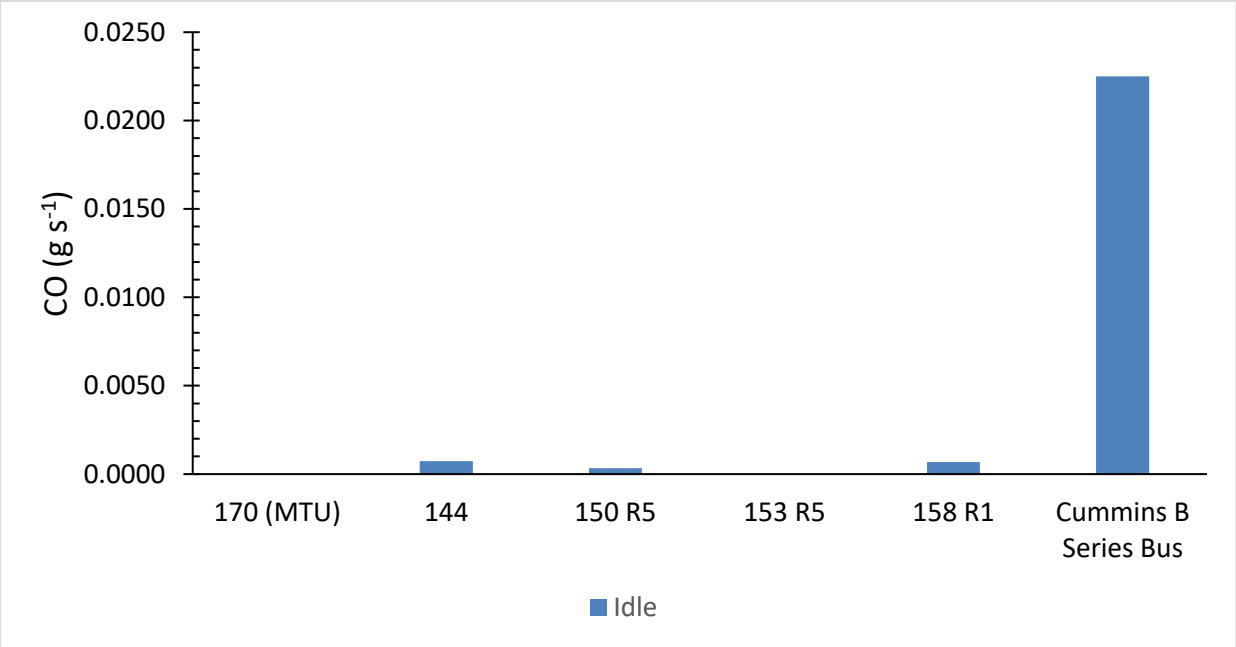


Figure 4.13 Comparison of CO mass flow rate of the DMUs of this study with Cummins bus engine emissions from literature (Toback et al., 2004)

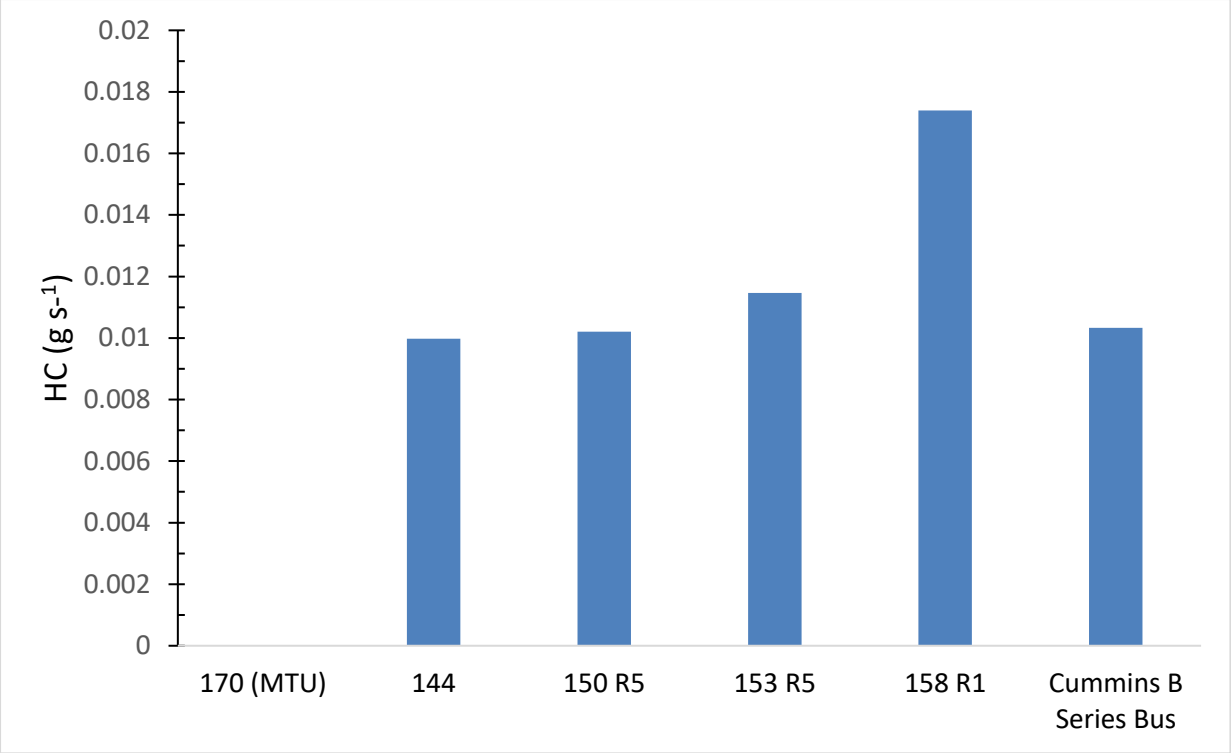


Figure 4.14 Comparison of HC mass flow rate of the DMUs of this study with Cummins bus engine emissions from literature (Toback et al., 2004)

4.2.11 Comparison of exhaust emission data of this study against 170 exhaust emission data on a mass flow rate basis

The three DMUs of this study were compared against a slightly, newer train of the 170 DMU, for the species of NO_x as seen in Figure 4.15. It was observed that the 15X DMUs have lower mass flow rates than the 170 DMU for both NO_x and CO_2. This can be attributed to several reasons: first the difference in testing regime, with the 170 DMU, the test conducted by the RSSB involved applied load on the engine following the testing procedure of ISO 8187:C1, whereas the 15X DMUs were tested without load, in a static position, and so this can potentially result in lower emissions than would have been observed with a load bank emission test.

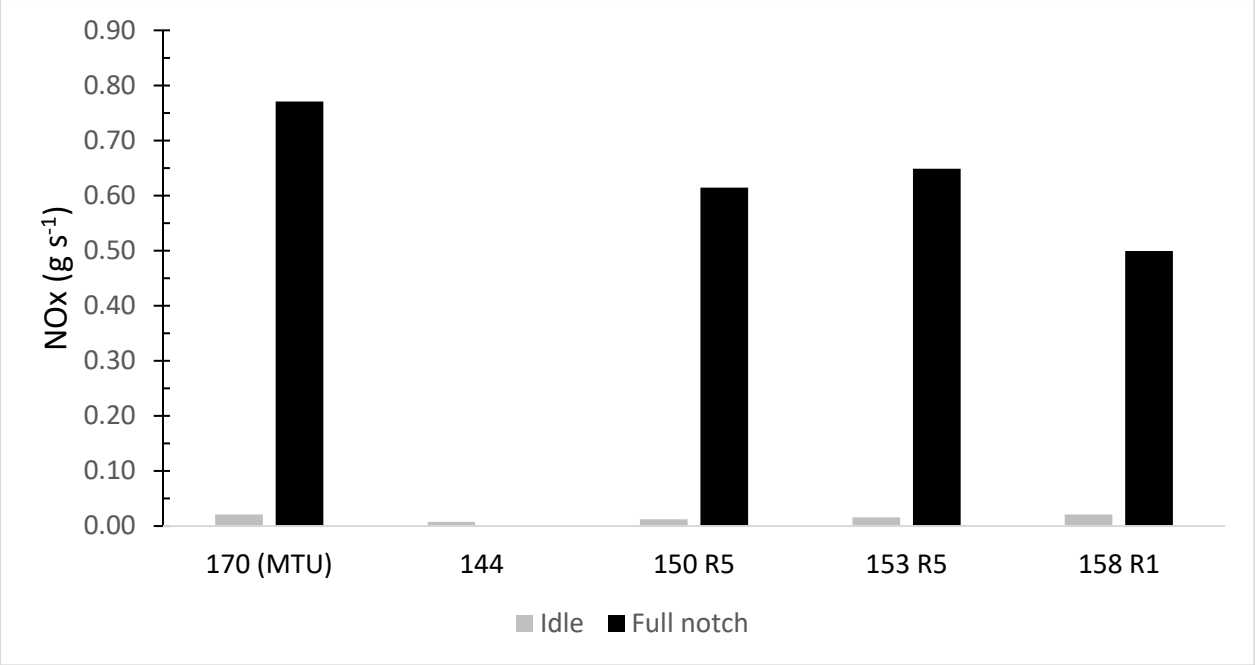


Figure 4.15 Comparison of NO_x mass flow rate of the DMUs of this study with external data from a 170 DMU

Secondly, the exhaust temperature of the 170 DMU is higher than the 15X DMUs of this study indicating a likelihood of greater complete combustion with the 170 DMU, and so a greater CO_2 mass flow rate is expected with the 170 DMUs. The effect of AFR on the NO_x and CO_2 flow rates is less consistent, with no effect at idle, with the 158 DMU (AFR: 95) having a lower AFR than the 170 DMU (AFR: 126) Thirdly, a much lower AFR ratio of 19 at full notch, with the 170 DMU is another reason that can be attributed for the higher NO_x and CO_2 mass flow rates in contrast to the higher AFR of 31-36 observed with the 15X DMUs of this study, as seen in Table 4.15. It must also be noted that the difference between the NO_x mass flow rates of 170 DMU and the 15X DMUs at both idle and full power are much smaller than the same comparison using the CO_2 mass flow rates, indicating an improvement of combustion with the 170 DMU as seen in Figure 4.16.

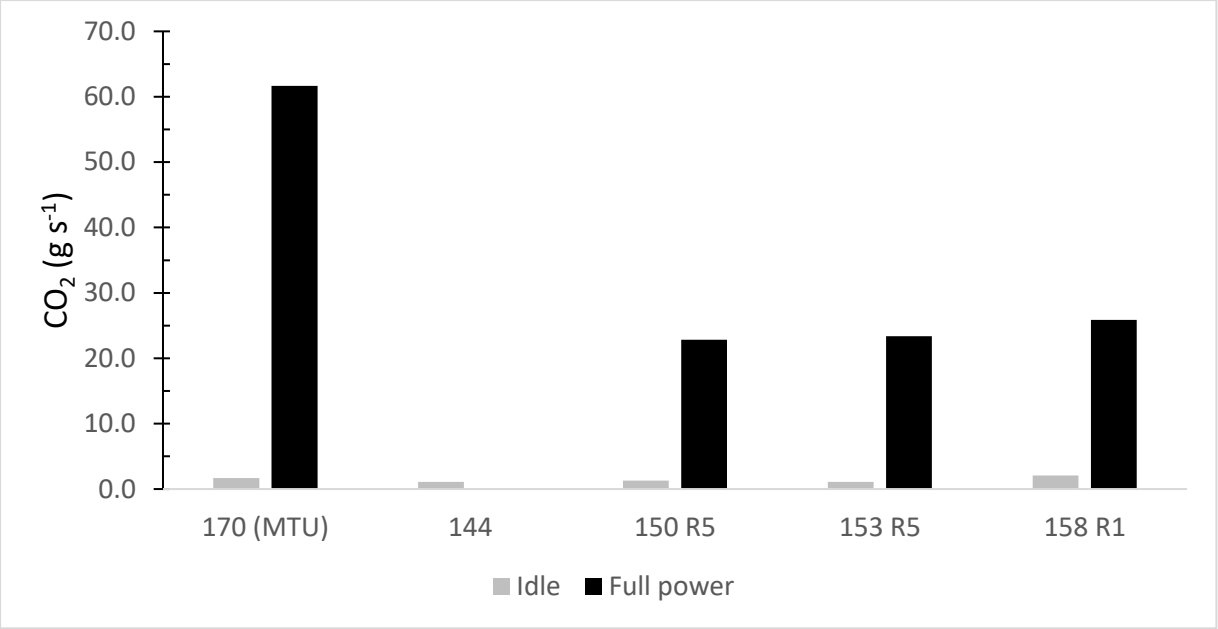


Figure 4.16 Comparison of CO_2 mass flow rate of the DMUs of this study with external data from a 170 DMU

Table 4.15 AFR comparison between the 170 and the 3 DMUs of this study

DMU	AFR (idle)	AFR (full notch)	T_e (°C) idle	T_e (°C) full notch	NO_x (idle) g s^{-1}	NO_x (full notch) g s^{-1}
150	136	36	184	267	0.01	0.61
153	165	35	240	293	0.02	0.65
158	95	31	228	321	0.02	0.50
170	126	19	150	660	0.02	0.77

To conclude this sub-section, the DMUs of this study have lower NO_x emissions than commercially tested similar-sized engines, such as the Caterpillar C12 bus engine of sub-section of 4.2.8 and the RSSB 170 DMU of sub-sections 4.2.10 and 4.2.11. This answers research question 1, in first determining the emission of the DMUs of this study, as concentration, emission index and mass emission rate, and then secondly comparing these against similar-sized engines in literature. This data however, only represents the combustion phase of diesel operation within an engine. In order to assess the total emissions of diesel across the fuel supply chain, a WTW analysis must be conducted and this is conducted in

the next section, in which diesel is compared against the alternative fuels HVO and GTL by means of a WTW assessment.

4.3 Well to Wheels emissions of fuels utilised in rail vehicles

4.3.1 Overview

In the earlier chapter of the literature review, alternative fuels, such as HVO (Hydrogenated Vegetable Oil) and GTL (Gas to Liquids) presented a number of advantageous properties in terms of air quality and carbon benefits in contrast to conventional diesel. GTL was reported to reduce the quantity of NO_x, PM and unburnt hydrocarbons, presenting numerous air quality benefits in addition to a reduction of 4% in combustion CO_2 emissions (Robert, 2020b). HVO presented similar benefits, with reductions in NO_x, PM and unburnt hydrocarbons, presenting numerous air quality benefits and well as a similar reduction of 4% in CO_2 combustion emissions (Suarez-Bertoa et al., 2019). These benefits were however, primarily defined within the engine combustion phase, i.e. downstream of the production phase of the fuel, or TTW (Tank-to-Wheel). In this section, the goal of this study is to assess both the upstream (Well to Tank (WTT)) and downstream (TTW) life cycle impacts of replacing diesel with either HVO or GTL, in a typical DMU UK rail vehicle. The boundary of the study is limited to a Well-to-Wheel (WTW) study. The functional unit for the study is 1 p-km (passenger-km). The goal of the study is to determine the WTW NO_x, PM_{10} and GHG in g p-km^{-1} for diesel, GTL and HVO.

In this section, by analysing the combustion emissions, for both diesel and alternative fuels, as one part of the WTW, potential improvements in DMU engine exhaust emissions. The WTW analysis of this study, evaluated diesel against two alternative fuels: GTL and HVO, to assess what the life cycle impacts are to introducing these alternative fuels in the fuel supply chain as a replacement for low sulphur diesel within a single carriage 150 DMU; addressing research question 3 (I., 2006b). HVO was considered in two feedstocks, Canola HVO and UCO HVO. In total, 4 fuels were evaluated: low sulphur diesel, Canola HVO, UCO HVO and GTL. The WTW was conducted using the GREET software package. The GREET internal template of Commuter Rail: Diesel + Electricity was utilised as the template for the WTW assessment of this study. Modifications were made to the GREET to reflect a UK DMU instead of a US commuter rail train. This included replacing the diesel emission factors for NO_x, PM, CO, CH_4 and VOC in (g v-km^{-1}) with data from the RSSB's T1187 report for the 150 DMU, as seen in Table 4.16 (Grennan-Heaven and

Gibbs, 2020b). It has been assumed that there is 100% occupancy on the DMUs, which represents the best scenario. Consequently the v-km (vehicle km) are equivalent to pkm (passenger km) as shown in equation 4.6 (IEA, 2021). GREET requires data to be inputted as p-km, and so this conversion was necessary to use the train data in GREET.

$$pkm = v\text{-}km \times \%Oc \quad (4.6)$$

where pkm is passenger km, v-km is the distance travelled in vehicle km, %Oc is the passenger occupancy of the DMU

For N_2O (nitrous oxide), POC (primary organic carbon) and BC (black carbon), default values from GREET for emission factors in g p-km^{-1} were used, due to a lack of available data for UK DMUs. The electricity inputs were set to zero, since the DMUs are 100% diesel powered only, and are not bi-mode trains. Limited publically available data in DMU engine combustion emission factors for alternative fuels, such as HVO and GTL, mean that appropriate scaling factors have been used in this chapter to estimate the NO_x, PM_{10} and CO_2 emission factors based on the % reduction in gaseous/particulate concentrations from literature with respect to diesel. This was previously outlined in the literature review (Chapter 2).

Table 4.16 Distance based emission factors in g v-km^{-1} for UK DMUs (Grennan-Heaven and Gibbs, 2020c)

Train class	**150**	**153**	**155**	**156**	**158**	**159**
CO (g v-km^{-1})	1.6	1.6	1.4	1.5	2.1	2.2
NO_x (g v-km^{-1})	5.2	5.2	5.2	5.2	3.9	3.9
HC (g v-km^{-1})	0.3	0.3	0.2	0.2	1.1	1.1
NMVOC (g v-km^{-1})	0.3	0.3	0.2	0.2	1	1.1
CH_4 (g v-km^{-1})	0	0	0	0	0	0
PM_{10} (g v-km^{-1})	0.08	0.08	0.08	0.08	0.52	0.52

Using Equation 4.7, the average energy consumption in kWh km^{-1} was determined for a typical 150 DMU. The parameters for Equation 4.7 are taken from Table 4.18.

$$Co = \frac{EA}{d\ NDMU} \quad (4.7)$$

where Co is the average consumption in kWh km^{-1} per 150 DMU, d is the annual distance in km travelled by the entire 150 DMU fleet of Northern Rail, EA in kWh is

the annual energy use of the entire 150 DMU fleet of Northern Rail and N_{DMU} is the total number of 150 DMUs in use by Northern Rail.

Table 4.17 Total annual 150 DMU consumption data obtained from Northern Rail internal monitoring (Gray, 2019)

DMU	d(km)	E(kWh)	N_{DMU}
150	20951549	104188586	162

Equation 4.7 determined an average km consumption of 0.031 kWh km^{-1} for a typical 150 DMU. The average consumption was used with the distance based emission factors from Table 4.16 as inputs for the GREET for the WTW determination of diesel fuel in a DMU. The full list of inputs for GREET are provided in Table 4.18.

Table 4.18 GREET input parameters for WTW model (GREET, 2020a; GREET, 2020c; GREET, 2020d; GREET, 2020b)

Parameter	
Fuel Consumption (kWh km^{-1})	0.031 [1]
VOC (g km^{-1})	0.3 [2]
CO (g km^{-1})	1.6 [2]
NO_x (g km^{-1})	5.2 [2]
PM_{10} (g km^{-1})	0.08 [2]
$PM_{2.5}$ (g km^{-1})	0.056 [3]
CH_4 (g km^{-1})	0[3]
N_2O (g km^{-1})	0.36
BC (g km^{-1})	0
POC (g km^{-1})	0

[1] From Table 4.17

[2] Grennan-Heaven and Gibbs (Grennan-Heaven and Gibbs, 2020b)

[3] Calculated used a correction factor of 0.7 from LAQM TG16 guidance (DEFRA, 2021)

[4] GREET default values for Commuter Rail: Diesel + Electricity

4.3.2 WTW NO_x

Using the GREET software, WTT NO_x data was obtained for the 4 fuels considered in this WTW assessment. In addition TTW data for low sulphur diesel was also obtained from GREET. Using Equation 4.8, the TTW NO_x emissions for the 3 alternative fuels of Canola HVO, GTL and UCO HVO, were estimated.

$$TTW_{alternative\ fuel,NOx}(g\ pkm^{-1}) = TTW_{diesel,NOx}(g\ pkm^{-1}) \times (1 - fCh_{NOx}) \quad (4.8)$$

where $TTW_{alternative\ fuel,NOx}(g\ pkm^{-1})$ is the Tank-to-Wheel distance based NOx emission factor of alternative fuels for a given species, $TTW_{diesel,NOx}(g\ pkm^{-1})$ is the Tank-to-Wheel distance based NO_x emission factor of low sulphur diesel fuel for a given species and fCh_{NOx} is the fractional change in exhaust NO_x emissions between low sulphur diesel and an alternative fuel (Canola HVO = 0.05, GTL= 0.06, UCO HVO = 0.05) (Aatola et al., 2008; Certas, 2019)

From Table 4.19, it is noted that GTL has the lowest WTW NO_x footprint in the WTW assessment. This is driven by the dominance of the combustion stage which comprises the majority of the emission in the WTW cycle as seen in Table 4.20. HVO also demonstrates a reduction in WTW NO_x for both Canola derived HVO and UCO derived HVO. The reduction in NO_x emissions with UCO HVO, according to literature can be attributed to the lower adiabatic flame temperature of HVO and a shorter ignition delay time, and so there is less time spent in the engine to generate the quantities NO_x normally observed with diesel fuel (Wu, 2019). In addition UCO HVO, using a feedstock of UCO, is a repurposed feedstock from waste chemicals and therefore has no extraction emissions. A percentage breakdown of the individual stages of the WTW emissions are provided in Table 4.21. The changes in WTW NO_x between the 3 fuels is shown in Figure 4.17.

Table 4.19 Estimated WTW NO_x distance based emission factors for diesel and alternative fuels for each stage of the WTW

	Extraction	Transportation	Production	Combustion	WTW
	g p-km^{-1}	g p-km^{-1}	g p-km^{-1}	g p-km^{-1}	g p-km^{-1}
Low sulphur diesel	0	0.001	0.002	5.200	5.203
Canola HVO	0.003	0	0.001	4.940	4.945
GTL from non-US natural gas	0.001	0	0.001	4.888	4.890
UCO HVO	0	0	0.001	4.940	4.942

Table 4.20 Percentage of individual stages of NO_x WTW total emissions

	WTT/WTW			TTW/WTW
Fuels	Extraction (%)	Transportation (%)	Production (%)	Combustion (%)
Low sulphur diesel	0.01	0.01	0.03	99.9
Canola HVO	0.07	0.01	0.02	99.9
GTL from non-US natural gas	0.02	0	0.01	100
UCO HVO	0	0.01	0.03	100

Table 4.21 Estimated NO_x WTW for diesel and alternative fuels for use in a single carriage 15X train with a Cummins NTA855 R5 engine

Fuels	WTT[1]	TTW	WTW	Improvement over diesel
	g p-km^{-1}	g p-km^{-1}	g p-km^{-1}	%
Low sulphur diesel	0.003[1]	5.200[1]	5.203	
Canola HVO	0.004[1]	4.940[2]	4.945	5
GTL from non-US natural gas	0.002[1]	4.888[3]	4.890	6
UCO HVO	0[1]	4.940[4]	4.942	5

1 From GREET internal database, 2 Estimated using Equation 4.8 with fCh_{NOx} = 0.05 (Aatola et al., 2008), 3 Estimated using Equation 4.8 with fCh_{NOx} = 0.06 (Certas, 2019), 4 Estimated using Equation 4.8 with fCh_{NOx} = 0.05 (Aatola et al., 2008)

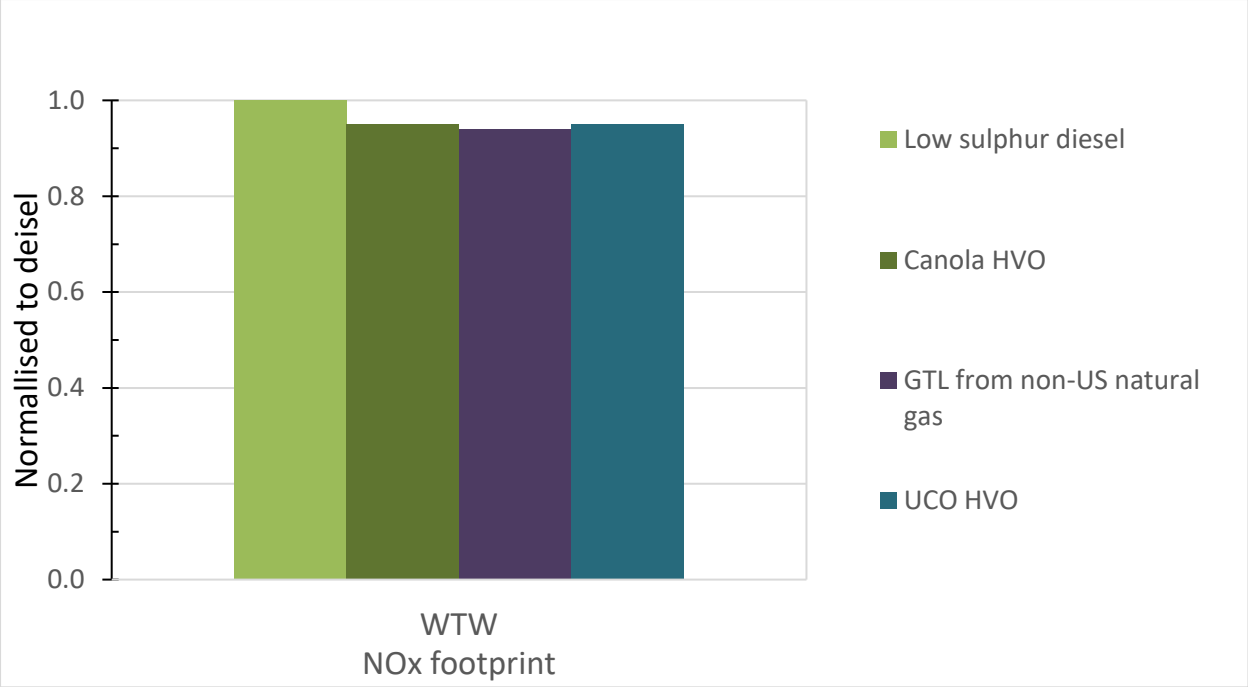


Figure 4.17 Comparison of the normalised diesel results for WTW NO_x footprint for fuels for use a single carriage 15X train with a Cummins NTA855 R5 engine

4.3.3 WTW PM_{10}

Using the GREET software, WTT PM_{10} data was obtained for the 4 fuels considered in this WTW assessment. In addition TTW data for low sulphur diesel was also obtained from GREET. Using Equation 4.9, the PM_{10} TTW emissions for the 3 fuels of Canola HVO, GTL and UCO HVO, were estimated.

$$TTW_{alternative\ fuel,PM10}(g\ pkm^{-1}) = TTW_{diesel,PM10}(g\ pkm^{-1}) \times (1 - fCh_{PM10}) \quad (4.9)$$

where $TTW_{alternative\ fuel}(g\ pkm^{-1})$ is the Tank-to-Wheel distance based PM_{10} emission factor of alternative fuels for a given species, $TTW_{diesel}(g\ pkm^{-1})$ is the Tank-to-Wheel distance based PM_{10} emission factor of low sulphur diesel fuel for a given species and fCh_{PM10} is the fractional change in exhaust PM_{10} emissions between low sulphur diesel and an alternative fuel (Canola HVO = 0.42, GTL = 0.28, UCO HVO = 0.42) (Honkanen et al., 2011; Certas, 2019)

As seen from Table 4.22, the WTW PM_{10} emissions are dominated by combustion emissions from the TTW phase. A percentage breakdown of the individual stages of the WTW emissions are provided in Table 4.23. GTL has the lowest PM_{10} WTW based on data from GREET and can be attributed to lower combustion PM_{10} emission than the other 3 fuels in the WTW assessment, combined with near zero extraction and production emissions, as seen in Table 4.24. Figure 4.18 illustrates

the difference in WTW PM_{10} emissions for the alternative fuels as compared against low sulphur diesel. It can be seen clearly that on a WTW basis, there are improvements in WTW PM_{10} using alternative fuels, with HVO (with either feedstock) and GTL both showing reductions in WTW PM_{10}. The changes in WTW PM_{10} between the 3 fuels is shown in Figure 4.18.

Table 4.22 Estimated WTW PM_{10} distance based emission factors for diesel and alternative fuels for each stage of the WTW

	Extraction	Transportation	Production	Combustion	WTW
	g p-km^{-1}	g p-km^{-1}	g p-km^{-1}	g p-km^{-1}	g p-km^{-1}
Low sulphur diesel	0	0	0	0.080	0.080
Canola HVO	0.002	0	0.001	0.05	0.049
GTL from non-US natural gas	0	0.001	0	0.06	0.059
UCO HVO	0	0	0	0.05	0.047

Table 4.23 Percentage of individual stages of PM_{10} WTW total emissions

	WTT/WTW			TTW/WTW
	Extraction (%)	Transportation (%)	Production (%)	Combustion (%)
Low sulphur diesel	0.02	0	0.23	99.8
Canola HVO	4.10	0	1.10	94.4
GTL from non-US natural gas	0.32		0.46	97.8
UCO HVO	0	0	0.60	99.3

Table 4.24 Estimated PM_{10} WTW for a single carriage 15X train with a Cummins NTA855 R5 engine

	WTT[1]	TTW	WTW	%Improvement over diesel
	g p-km^{-1}	g p-km^{-1}	g p-km^{-1}	%
Low sulphur diesel	0[1]	0.080[1]	0.080	
Canola HVO	0.003[1]	0.046[2]	0.049	39
GTL from non-US natural gas	0.001[1]	0.058[3]	0.059	27
UCO HVO	0[1]	0.046[4]	0.047	42

1 From GREET internal database, 2 Estimated using Equation 4.9 with fCh_{PM10} = 0.42 (Honkanen et al., 2011), 3 Estimated using Equation 4.9 with fCh_{PM10} = 0.28 (Certas, 2019; DB, 2015), 4 Estimated using Equation 4.9 with fCh_{PM10} = 0.42 (Honkanen et al., 2011)

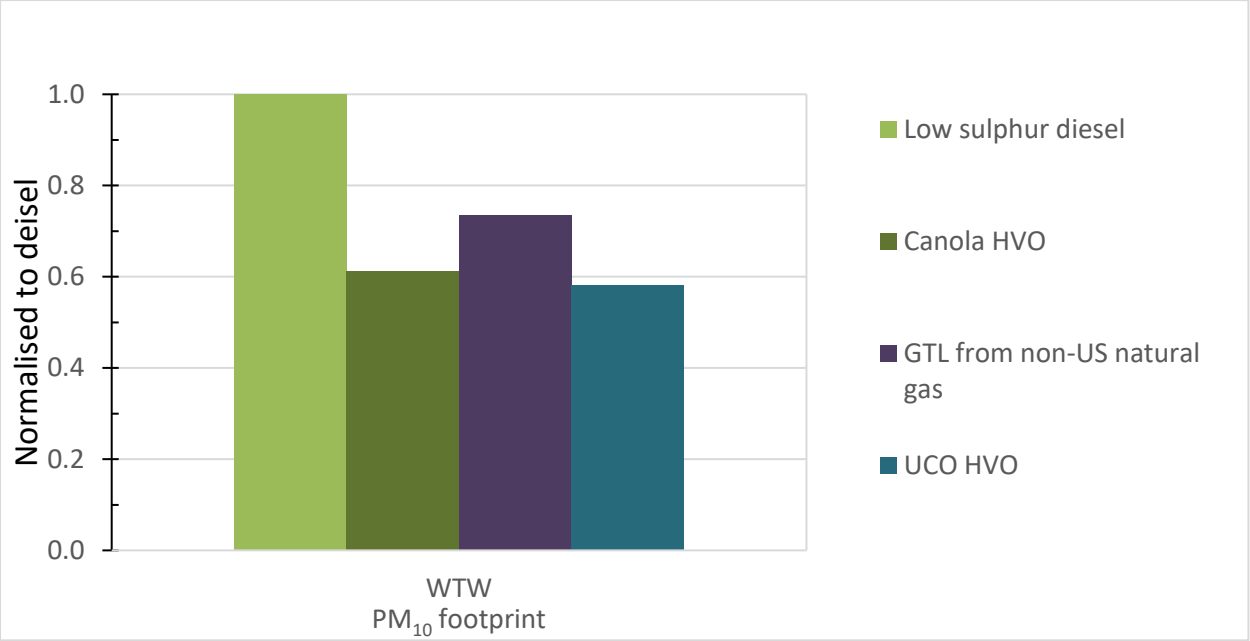


Figure 4.18 Comparison of the normalised WTW diesel results for PM_{10} footprint for fuels for use in a single carriage 15X train with a Cummins NTA855 R5 engine

4.3.4 WTW GHG

Using the GREET software, WTT GHG data was obtained for the 4 fuels considered in this WTW assessment. In addition TTW data for low sulphur diesel was also obtained from GREET. Using Equation 4.10, the GHG TTW emissions for the 3 alternative fuels of Canola HVO, GTL and UCO HVO, were estimated. For Canola HVO and UCO, HVO, the TTW emissions were assumed to be zero, with all of the CO_2 generated in the combustion phase offset by new trees planted (Robert, 2020a)

$$TTW_{alternative\ fuel,GHG}(g\ pkm^{-1}) = TTW_{diesel,GHG}(g\ pkm^{-1}) \times (1 - fCh_{GHG}) \qquad (4.10)$$

where $TTW_{alternative\ fuel,GHG}(g\ pkm^{-1})$ is the Tank-to-Wheel distance based GHG emission factor of alternative fuels for a given species, $TTW_{diesel,GHG}(g\ pkm^{-1})$ is the Tank-to-Wheel distance based GHG emission factor of low sulphur diesel fuel for a given species and fCh_{GHG} is the fractional change in exhaust GHG emissions between low sulphur diesel and an alternative fuel (Canola HVO = 0.04, GTL=0.04, UCO HVO = 0.04) (Suarez-Bertoa et al., 2019; Robert, 2020b)

For the WTW assessment, of the 4 fuels, the GHG emissions from the combustion phase (TTW) is very small in comparison to the upstream WTT process in the fuel

supply chain, as seen in . A percentage breakdown of the individual stages of the WTW emissions are provided in Table 4.26. UCO HVO has the lowest GHG reduction with significant reductions in GHG emissions on a WTW basis, when compared against low sulphur diesel, with a 91% reduction. This GHG WTW reduction can be attributed to two factors, the zero combustion emissions of UCO HVO due its' biogenic content, and the zero extraction emissions for UCO HVO, as it is a waste product (from other industries) repurposed as a feedstock for fuel production, and so has no extraction emissions. Canola HVO, also showed a decrease in GHG emissions as seen in Figure 4.19, like UCO HVO, its' zero combustion emissions, arising from the biogenic content of Canola HVO, consequently reduced the total WTW GHG emissions of UCO HVO by 82%. It has a slightly higher GHG than UCO HVO and this is due a large quantity of GHG in the extraction phase of the WTW, in extracting the canola oil from canola seeds. GTL demonstrates minor reductions WTW GHG footprint with a 9% reduction in WTW emissions than low sulphur diesel as seen in Table 4.27, with the production phase of generating GTL from natural gas via the Fischer-Tropsch process, much lower in GHG, according to simulations in GREET, than the fractional distillation of crude oil into diesel, for low sulphur diesel production.

Table 4.25 Estimated WTW GHG distance based emission factors for diesel and alternative fuels for each stage of the WTW

	Extraction	Transportation	Production	Combustion	WTW
	g p-km^{-1}	g p-km^{-1}	g p-km^{-1}	g p-km^{-1}	g p-km^{-1}
Low sulphur diesel	0.194[1]	0.273[1]	1.180[1]	8.220[1]	9.867
Canola HVO	1.342[1]	0.115[1]	0.359[1]	0[4]	1.816
GTL from non-US natural gas	0.313[1]	0.100[1]	0.433[1]	8.117[3]	8.963
UCO HVO	0[2]	0.131[1]	0.772[1]	0[4]	0.903

1 From GREET internal database

2 Zero due to biogenic content (Robert, 2020a)

3 Estimated using Equation 4.10 with fCh_{GHG} (GTL) = 0.04 (Robert, 2020b)

4 Zero due to biogenic content (Robert, 2020a)

Table 4.26 Percentage of individual stages of GHG WTW total emissions

	WTT/WTW			TTW/WTW (including biogenic content)
	Extraction (%)	Transportation (%)	Production (%)	Combustion (%)
Low sulphur diesel	2	3	12	83
Canola HVO	74	6	20	0[1]
GTL from non-US natural gas	3	1	5	91
UCO HVO	0	15	85	0[1]

1 Zero due to the biogenic content of HVO (Robert, 2020a)

Table 4.27 Estimated GHG WTW for a single carriage 150 DMU with a Cummins NTA855 R5 engine

	WTT	TTW	Biogenic content	WTW	Improvement over diesel
	g p-km^{-1}	g p-km^{-1}	g p-km^{-1}	g p-km^{-1}	%
Low sulphur diesel	1.65[1]	8.22[1]	0	9.87	
Canola HVO	1.82[1]	0		1.82	82
GTL from non-US natural gas	0.85[1]	8.12[3]	0	8.96	9
UCO HVO	0.90[1]	0		0.90	91

1 From GREET internal database, 2 Estimated using Equation 4.10 with fCh_{GHG} (Canola HVO) = 0.04 (Suarez-Bertoa et al., 2019) 3 Estimated using Equation 4.10 with fCh_{GHG} (GTL) = 0.04 (Robert, 2020b), 4 Estimated using Equation 4.10 with fCh_{GHG} (UCO HVO) = 0.04

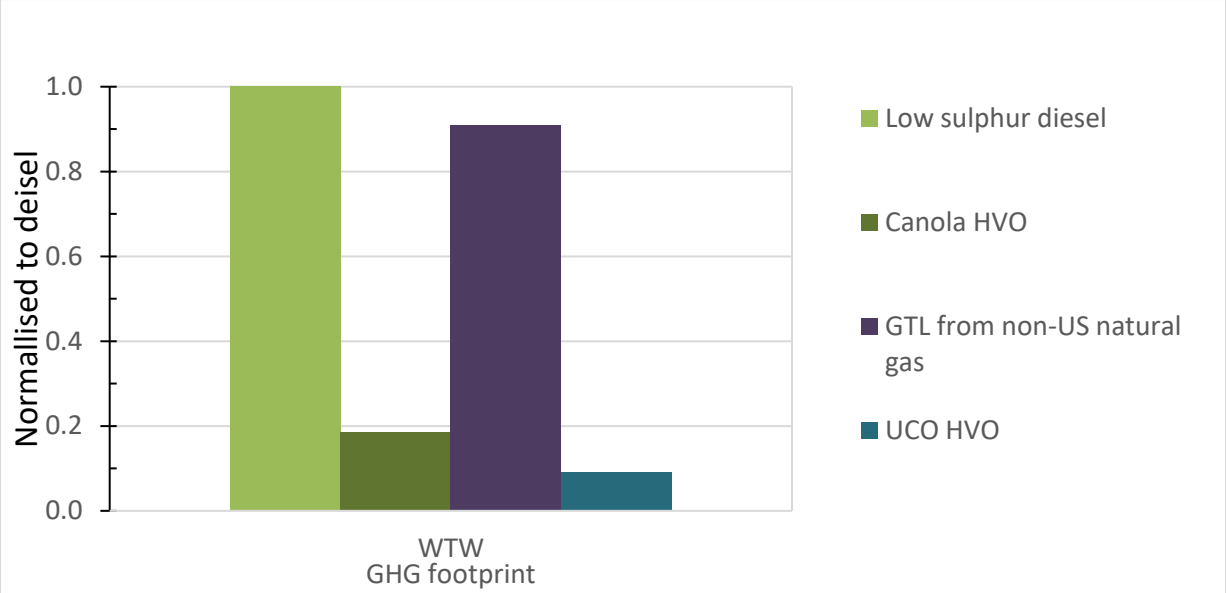


Figure 4.19 Comparison of the normalised WTW diesel results for GHG footprint for fuels for use in a single carriage 15X DMU with a Cummins NTA855 R5 engine

The WTW life cycle analysis shows that UCO HVO, is the most promising alternative to diesel with minor improvements in NO_x (8%) and GHG (45%) on a WTW basis, however, increases in WTW PM_{10} (58%) are noted.

4.4 Current policy and the potential for alternative fuel use in rail

Following sub-section 4.3, which assessed the WTW emissions of Canola HVO, GTL and UCO HVO, showing some improvements in NO_x and GHG for these fuels on a WTW assessment. There are other factors which affect the introduction of alternative fuels into the UK rail sector, and this sub-section will affect these factors briefly and the current policy direction on using alternative fuels in UK rail, in line with research question 3:

R3: What factors need to be considered when introducing alternative fuels into diesel-powered trains?

The RSSB have published a policy statement in 2021 on the use and future use of alternative fuels, which include HVO, in the UK rail sector (Kluth, 2021). They note that alternative fuels have “no long-term role” on a “net zero carbon railway”. They also note that supply is limited for alternative fuels and that any supply is likely to be reserved for the aviation and road HGV sector. The RSSB’s policy direction is leaning more towards other technologies to decarbonise UK rail, both in the passenger and freight rail sectors. A number of potential options have been

presented in their T1145 (Options for traction energy decarbonisation in rail: options evaluation) report and these include:

1. “Electrification
2. Advanced hybrid diesel
3. Hydrogen fuel cell technology powered by brown H_2
4. Hydrogen fuel cells with H_2 produced from low Carbon/zero Carbon electricity,
5. Battery powered vehicles
6. Natural gas powered vehicles” (RSSB, 2018).

The CO_2 reduction benefits of these technologies are illustrated in Figure 4.20, with green hydrogen and biodiesel rated with zero carbon emissions and 2040 overhead electrification showing a significant reduction in CO_2-e emissions from 0.83 kg CO_2e kWh^{-1} to 0.16 kg CO_2e kWh^{-1} (RSSB, 2018). It is unclear at present which of these technologies will proceed for implementation, which is at the discretion of the Department for Transport and the UK Treasury.

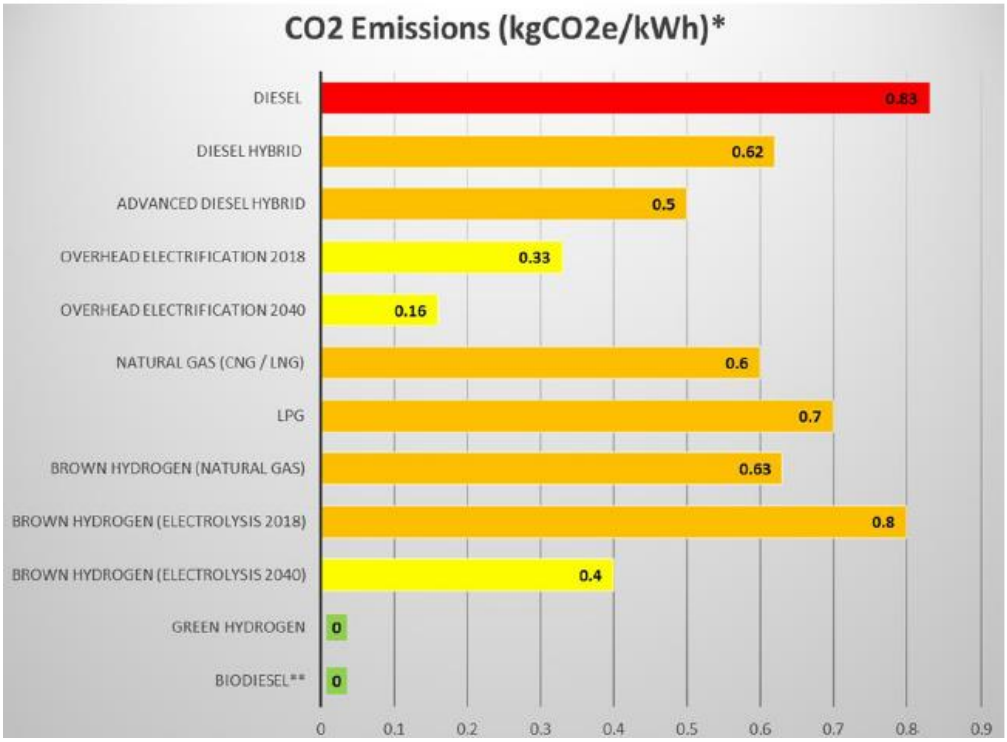


Figure 4.20 The RSSB’s options for potential CO_2 emissions reduction potential for UK rail (reproduced from the RSSB) (RSSB, 2018)

In terms of the freight sector, the RSSB, in follow-up work in their T1160 project (Decarbonisation and air quality improvement of the freight rail industry have at least presented a roadmap which could be used to decarbonise freight rail and improve air quality in the freight rail sector, which are presented in Figure 4.21 (RSSB and Ricardo, 2020). More concrete plans for the UK passenger rail sector are likely to be outlined in the RSSB's current T1227 (DECARB: Decarbonisation action plans) project in terms of UK passenger rail decarbonisation and T1233 (Air quality targets) for air quality improvement in UK passenger rail (RSSB, 2022a; RSSB, 2022b) .

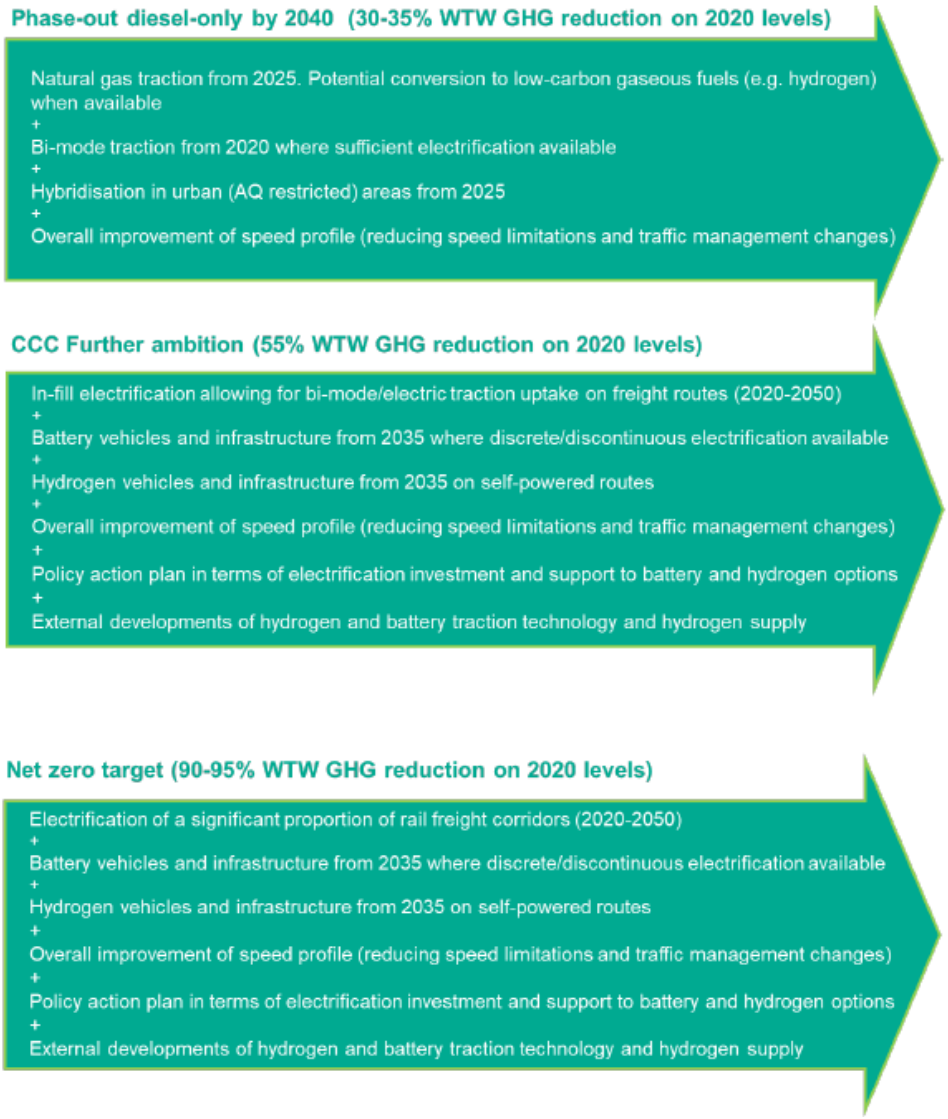


Figure 4.21 RSSB proposed roadmap for UK freight decarbonisation (reproduced from the RSSB)(RSSB and Ricardo, 2020)

The RSSB, although in their 2021 policy statement discourage non-diesel or alternative fuel use, it does however, acknowledge the ability of individual train operators to deploy alternative fuels, if they so choose, "to achieve immediate carbon

savings" (Kluth, 2021). As covered in this sub-section 4.3.4, UCO HVO showed promise as an option to decarbonise diesel vehicles, such as DMUs in the UK rail sector, with significant reductions (~50%) in GHG on a WTW basis vs. current in-use low-sulphur diesel.

There are however, other factors which affect the potential for alternative fuel use in UK rail, cost is one such key factor in determining the viability of fuels such as GTL and HVO within rail. The cost per litre of alternative fuels in the UK, as well as price of low sulphur diesel for rail also known as 'red diesel', is provided in Table 4.28 (see Appendix E for further details) (Energy, 2020). As seen in Table 4.28, in contrast to the currently used red-dyed version of low sulphur diesel (red diesel) deployed in diesel vehicles on the UK rail network, GTL and HVO are more expensive fuels than red diesel on a per litre basis. In the case of GTL, the cost of litre is almost 25% higher than red diesel and in the case of HVO, the cost is nearly double the cost of red diesel. This increase in cost is a disincentive to switch from red diesel, in particular TOC's such as Northern Rail, have a diesel fuel litre usage of 40874646 l, this represents a significant increase in opening costs per year as noted in Table 4.29.

Table 4.28 Cost estimation for the annual cost of using an alternative fuel within Northern's DMU fleet (EIBIP; Gov; Bioukfuels; RAC, 2019)

	Cost (£/litre)
Low Sulphur Diesel (Red Diesel)[1]	0.38
GTL[2]	0.475
HVO[2]	0.725

[1]Internal data Northern Rail as of July 2020

[2]Certas Energy as of July 2020

Table 4.29 Estimated increase in annual costs using alternative fuels instead of diesel

	Estimated Annual Cost (£)	% Increase in Cost
Low Sulphur Diesel (Red Diesel)	£15,532,365	
GTL	£19,415,457	25%
HVO	£29,634,118	91%

Availability of these alternative fuels, is another factor affecting their potential for deployment. As noted previously by the RSSB, the supply of available alternative fuels is limited, and is in demand by other transportation sectors, including the aviation and HGV sector (Kluth, 2021). A growing demand, for using sustainable aviation fuel (SAF) in a blend with jet fuel, depresses the amount of HVO available for rail, since SAF is derived in some cases from an upgraded form of HVO, from used cooking oil feedstock (Carroll, 2022; DfT, 2021b). Another issue is that the demand for used cooking oil, is leading to unsustainable varieties of used cooking oil, derived from palm oil entering the commercial market, from palm oil producing countries such as Malaysia and Indonesia (McGrath, 2021; Otley, 2022). Weak regulation, both in the UK and the EU, makes it difficult for buyers such as train companies to determine whether their HVO is derived from a sustainable feedstock, as noted by the Transport & Environment UCO briefing (Mestre, 2021). They note, that in the case of the EU, three problems: firstly 'low transparency along the supply chains', secondly, low traceability down to the point of origin and thirdly, lack of verification in the voluntary schemes and fourthly, opportunity for double counting' (Mestre, 2021).

From this chapter, four factors have been determined that affect the introduction of alternative fuels into the rail sector as a decarbonisation tool. These are WTW emissions, cost, availability and sustainability. This answers research question 3 in determining the WTW life cycle impacts of introducing alternative fuels into diesel powered trains. Whilst UCO HVO is the best option in terms of WTW emission vs. conventional red diesel due its' to biogenic credit, there are significant disincentives to UCO HVO in terms of an increased cost, limited supply and difficulty in purchasing truly sustainable UCO HVO, not derived from palm oil. Some train operators have already conducted trials on UCO HVO, with one of the freight operating companies (FOC), DB Cargo UK, in 2021 trialling the use of HVO within their Class 66 and Class 77 freight vehicles at the Toton railway depot in the East Midlands (DBCargo, 2021). DB Cargo presented this trial as an opportunity to both decarbonise their freight fleet as well to reduce NO_x diesel exhaust emissions (DBCargo, 2021). It was claimed by DB Cargo that in terms of decarbonisation, the UCO HVO used in their fleet could 'minimise CO_2 emissions by up to 90%'. From the work in this study, it is most likely this claimed 90% CO_2 emissions reduction by DB Cargo is a WTW CO_2-e reduction of 90%, where in this study a 91% WTW CO_2-e reduction was determined for UCO HVO.

In terms of GTL, it is cheaper in price than HVO per litre (as of July 2020 data) at £0.48 vs. £0.73 (for HVO), however it is also more expensive than red diesel, at

£0.38 (as of July 2020) used in diesel rail. As a fossil fuel derived fuel, it does not have the biogenic benefits of HVO and is also not a sustainable fuel, as it derived from natural gas. In terms of supply, it suffers similar problems to HVO, competing with road and air transport sectors, in particular the HGV sector looking to also utilise GTL to decarbonise their transport sector. This reduces the amount of available GTL fuel, for rail, which requires a high volume of fuel annually for operations, with Northern Rail, as an example, utilising 40874646 l/yr of red diesel in their fleet.

4.5 Conclusion

In this chapter, the mass emission rates of 3 DMUs (150142, 153378 and 158903) have been determined at idle notch and full notch, using a PEMS system inside a railway depot (Neville Hill) without applied load. The mass emission rates of these DMUs have been compared against NO_x (0.02-0.77 g s^{-1}) and CO_2 (1.7-61.7 g s^{-1}) mass emission rates from a 170 DMU, addressing research question 1. The data showed that the 170 DMU had higher NO_x and CO_2 mass emission rates at full power than the 15X DMUs of this study and this can be attributed to the larger fuel consumption of the 170 DMU. In a separate comparison, it was also noted that the 15X DMUs of this study had lower exhaust mass flow rates of NO_x (0.01-0.02 g s^{-1}) and CO_2 (1.10-2.06 g s^{-1}) at idle power than a similar sized Cummins bus engine vehicle (NO_x 0.03 g s^{-1} and CO_2 1.40 g s^{-1}), however, higher exhaust mass flow rates of HC were observed with the 15X DMUs.

With increasing notch, the decrease in AFR affects the concentrations of these species as seen when comparing the 3 DMUs, i.e. 150 vs 153 vs 158. When compared against data from 170 DMU, the exhaust temperature and thus engine load is the major driver for increasing concentrations as seen when comparing the 15X DMUs of this study against the RSSB's 170 DMU. There are caveats to this comparison, as the emission measurements from the DMUs were conducted without load, in contrast to literature data from the 170 DMU and the Cummins N21-bus engine. This in turn, can potentially result in lower emissions from the DMUs of this study than would have been observed with a load bank emission test. As a future work area, Frey and Graver have developed a methodology to factor for emission measurements conducted without the use of load, and this could be utilised to scale the DMU emission rates from this work for a better comparison against other similar engines, such as the RSSB's 170 DMU (Graver and Frey, 2013a).

Whilst the emission data from this work has not accounted for load, these same engines types, the Cummins NTA855 in the R1 and R3 variants have been tested previously by the RSSB with load in 2003 as discussed in the literature review of Chapter 2. In this the RSSB's measurements showed that average cycle notch in g/kWh for NO_x is only compliant to a very old advisory set by the UIC and is much higher than the current rail engine standard of EU Stage IIIB. This justifies the research into alternative fuels, to observe the effects of changing the fuel from diesel on the NO_x, PM10 and GHG emissions not only at source, but within the fuel life cycle.

In terms of the WTW analysis, three alternative fuels (GTL, Canola HVO and UCO HVO) have been assessed in a WTW study to quantify the life cycle impacts of replacing diesel fuel in 15X DMU train to evaluate research question 3. UCO HVO showed the most promising life cycle benefits with improvements in NO_x and GHG across the fuel supply chain. In addition, reductions in combustion emissions, for UCO HVO, with an estimated 5% reduction in exhaust NO_x and 42% reduction in exhaust PM_{10}, make it a potential option to improve indoor air quality within railway depots via reduced diesel exhaust emissions. GTL also showed improvements in NOx (6%) and GHG (49%) across the fuel supply chain. It however, had significant increases in WTW PM_{10} emissions (556%) compared to low sulphur diesel. GTL similar to HVO also showed improvements in combustion emissions with a 6% reduction in NO_x and a 28% reduction in PM_{10}, also make an option to improve indoor air quality within depots. Canola HVO showed a reduction in WTW NO_x (3%), however, it had increases in both PM_{10} WTW (1272%) and GHG WTW (10%). Similar to UCO HVO, it showed improvements in combustion emissions with a 5% reduction in exhaust NO_x and a 42% reduction in exhaust PM_{10}.

Other factors however, such as cost, availability, sustainability and policy support acted as disincentives to the introduction of these fuels to replace alternative fuels, with often a higher price per litre vs. in-use red diesel for both fuels, with a 90% increase in fuel costs with HVO and a 25% increases in annual fuel costs with GTL. At present, the RSSB do not support the use of alternative fuels, and instead prefer electrification and hybridisation to improve air quality in the rail sector and decarbonise it at the same time. With no support from the RSSB, individual operators, such as Northern Rail, must cover the costs and liability, themselves, for the deployment of alternative fuels, within their fleet, which is a challenge, both economically and operationally.

In conclusion, this study has attributed the change in concentration for all of the species (CO, CO_2, NO, NO_2, NO_x, THC and PN) monitored from idle power to full

power, to two key factors: notch setting or engine power output and AFR answering research question 1. The introduction of alternative fuels into the UK rail sector is a complex issue, as noted in this chapter, with cost, availability, sustainability, policy support, WTW emissions and combustion emissions, all factors which influence the viability of introducing the alternative fuels of Canola HVO, GTL and UCO HVO into UK trains, thereby answering researching question 2 through the quantification of the WTW life cycle impacts and research question 3 by outlining additional factors which also affect the introduction of alternative fuels into UK rail. Further work will be carried out in Chapter 5, incorporating the emission rates of this chapter into a box model to determine the ventilation effectiveness within the same test area (the repair shed of the Neville Hill railway depot) as the DMU exhaust emission measurement.

Chapter 5 Static air quality monitoring in 4 UK railway depots and a station

5.1 Overview

This chapter assesses the air quality measurements of four railway depots (Neville Hill, Allerton, Heaton and Newton Heath) and one train station (Manchester Victoria) at fixed locations in order to address research question 4:

R4: What type of parameters affect the air quality of UK railway depots and train stations where diesel trains are in operation?

As part of this assessment, a number of scientific questions have been formulated to support research question 4 and are as follows:

SQ1. Are there seasonal variations in the indoor air quality within the railway depots of the study?

SQ2. Is there evidence of temperature gradient behaviour within any of the four railway depots of this study?

SQ3. Is there evidence of a pollution gradient within any of the four railway depots of this study?

SQ4. Are the main sheds of the railway depots in this study well-mixed?

SQ5. Are there seasonal variations in the indoor air quality within the Manchester Victoria train station of the study?

A number of experiments were conducted to evaluate research question 4. In sub-sections 5.2 and 5.3, this involved measuring the ground level indoor NO_2 concentration in four railway depots (Neville Hill, Allerton, Heaton and Newton Heath), to observe seasonal variations in the indoor NO_2 concentration. Sub-section 5.4, assessed the change in indoor NO_2 concentration and indoor temperature between Apr 2018 and May 2019 within the repair shed section of the Neville Hill railway depot, to investigate temperature gradients. Expanding on this, a time-variant box model was utilised in sub-section 5.5, to see if this repair shed was well-mixed, by comparing predicted NO_2 concentrations from the box model, against typical transient NO_2 concentrations for the repair shed, from a chemiluminescence analyser. Sub-section 5.6, looked for similar indications of a temperature gradient, within the three other railway depots of Allerton, Heaton and Newton Heath,

considered in this study. It must be noted that within these 3 railway depots, only the variations in changing height were monitored for indoor NO_2 concentration and no temperature measurements were conducted. Further details about these monitoring campaigns, have been outlined previously in the methodology chapter (Chapter 3). In sub-section 5.7, the diffusion tube NO_2 four-weekly concentrations were annualised for 2018 and 2019 for each of the four railway depots as per LAQM (Local Air Quality Management) TG22 guidance, to observe how the indoor NO_2 concentrations compare against the annual UK AQS NO_2 concentration limit of 40 µg m^{-3}, which applies for outdoor spaces (DEFRA; LAQM, 2022b). Sub-section 5.8, evaluated the indoor NO_2 ground concentrations within the Manchester Victoria, at platform level, on the platform concourse and within the station's passenger overbridge. The annualised NO_2 concentration data from the railway depots and the Manchester Victoria station of this study were then compared against other train stations and automatic and non-automatic monitoring sites as part of sub-section 5.8, in the context of research question 4.

5.2 Effect of seasonal variations on the ground level NO_2 concentrations within the repair shed section of the Neville Hill railway depot in Leeds

Static air quality monitoring, as mentioned earlier in the literature review (Chapter 1) is an assessment method for determining the averaged air quality concentration at a fixed location over a period of time e.g. 2-4 wks. Diffusion tubes are the cheapest and most widely used method for static air quality monitoring and offer the ability to identify spatial variations in air quality. In the Neville Hill railway depot, within one building, the repair shed, variations in seasonal indoor NO_2 concentration, were monitored, using four-weekly diffusion tube measurements, across a monitoring period between Apr 2018 – May 2019.

In the repair shed of the Neville Hill railway depot, the concentration of NO_2 at ground level, of 1.6 m, had a numerical average of 65 µg m^{-3} across the annual monitoring period Apr 2018 – May 2019. It must be noted that this numerical average is different from the annualised concentration as per LAQM TG122 guidance, which uses a diffusion tube calendar, that is roughly equivalent to a calendar year, typically offset by one week to avoid Christmas period diffusion tube installations (LAQM, 2021a). For simplicity in this study, a calendar year of 1st Jan 2018 - 31st Dec 2018 has been used for annualisation and is determined separately in sub-section 5.7

(DEFRA, 2018b). Relative bias correction for diffusion tubes is typically applied on annual averages of concentrations, and therefore is not appropriate for seasonal or monthly averages of NO_2 concentration. Therefore, the monthly NO_2 concentration data presented in sub-section 5.1-5.6 is uncorrected for relative bias. In sub-section 5.7, the annual NO_2 concentrations have been relative bias corrected and annualised (LAQM, 2021a). Table 5.1 presents the indoor NO_2 concentrations per season for the main shed of the Neville Hill railway depots between 2018 and 2019.

Table 5.1 Seasonal variations in indoor, ground-concentration NO_2 concentrations in the repair shed of the Neville Hill railway depot

Season	**Seasonal NO_2 concentration average (μg m^{-3})**	**Average ambient temperature[1] (°C)**
Spring 2018	45	8.0
Summer 2018	38	16.1
Autumn 2018	73	9.7
Winter 2018	94	5.2
Spring 2019	77	8.1

[1] Leeds Bradford weather station

The NO_2 seasonal concentration data of Table 5.1 shows that there are seasonal variations in the concentrations of NO_2 across the four seasons spanning spring 2018 to spring 2019 as seen in Figure 5.1, and answering the first scientific question, of investigating if there are seasonal variations in NO_2 in the railway depots, which in this railway depot location, of Neville Hill is true.

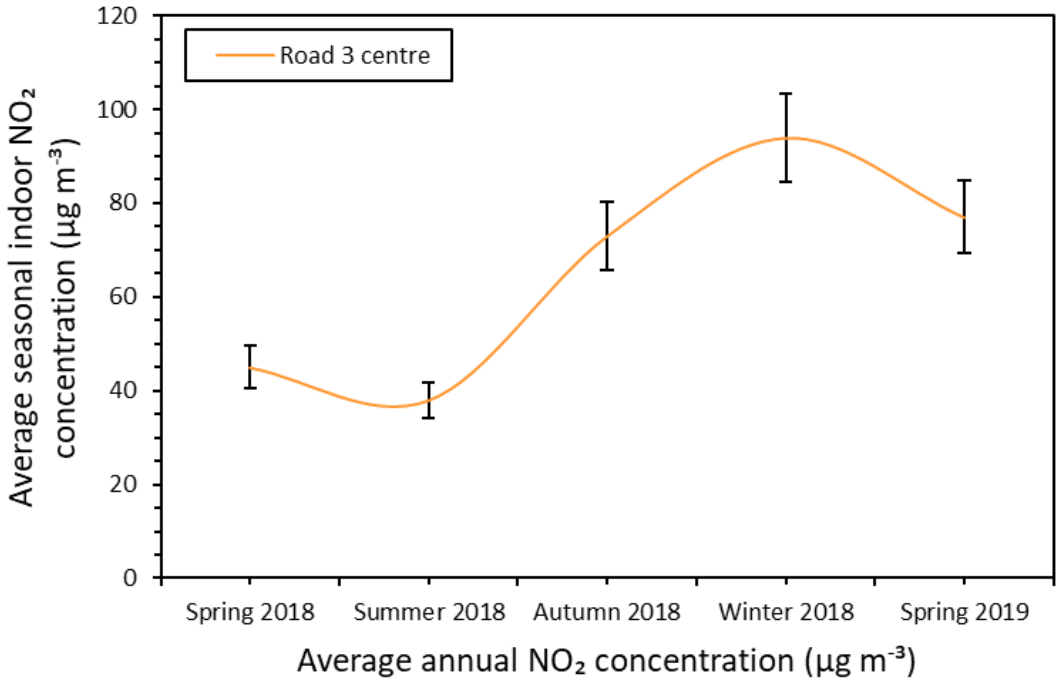


Figure 5.1 Illustration of the seasonal variations in indoor, ground-concentration NO_2 in the repair shed of the Neville Hill depot

In line, with research question 4, the changes in NO_2 concentrations with season, provides evidence that seasonal variation is one parameter which affects air quality in an indoor railway depot. The reason for the higher seasonal NO_2 concentrations in the winter periods, and lower concentrations in the summer periods can be attributed to the reduction in natural ventilation in the shed, as during the winter months the shed doors of the repair shed are closed to retain heat due to the ambient temperatures of 0-5°C. This means that in the winter months, the diesel fumes are solely extracted via the mechanical roof extraction system within the repair shed.

5.3 Effect of seasonal variations on the ground level concentration NO_2 concentration with railway depots located in Liverpool, Manchester and Newcastle

To further investigate the seasonal variations in NO_2 concentrations inside railway depots, the changes in indoor NO_2 concentrations were assessed within the highest maintenance activity area of the Allerton, Heaton and Newton Heath railway depots; located in Liverpool, Manchester and Newcastle respectively. This is to support the second scientific question of investigating the changes in concentration

within the four depots of this study and also the fourth scientist question whether any of the depot buildings are well-mixed or not.

5.3.1 Allerton Railway depot, Liverpool

The concentration data from the NO_2 diffusion tubes per season at the Allerton railway depot is presented in Table 5.2 with weather data obtained from the WorldMet R package (Carslaw, 2022). Similar to Neville Hill, the seasonal NO_2 concentrations were highest in the winter period of December 2018 – February 2019, closely followed by the autumn period months of 2018. At Allerton, there are fewer diesel trains maintained at the railway depot than the other railway depots considered in this study, due to approximately 60% of the capacity at the Allerton railway depot allocated for electric trains.

Table 5.2 Seasonal variations in indoor, ground-concentration NO_2 concentrations in the repair shed of the Allerton railway depot

Season	**Seasonal NO_2 concentration average (µg m^{-3})**	**Average ambient temperature[1] (°C)**
Spring 2018	-	-
Summer 2018	-	-
Autumn 2018	38	11.3
Winter 2018	47	6.8
Spring 2019	37	10.1

[1] Liverpool Airport weather station (Carslaw, 2022)

5.3.2 Heaton Railway depot, Newcastle

The seasonal concentration data from the NO_2 diffusion tubes at the Heaton railway depot is presented in Table 5.3 with weather data obtained from the WorldMet R package (Carslaw, 2022). As with the Neville Hill and Newton Heath NO_2 seasonal concentration data, a similar trend is noted with the seasonal NO_2 concentrations worst in the winter period months of 2018, spanning December 2018 – February 2019. The NO_2 concentrations are significantly higher than the other railway depots of Newton Heath, Neville Hill and Allerton, which can be attributed to the mix of diesel trains present at Heaton, which includes not only commuter trains

such as DMU, which are considered in this study, but also at the time of measurement, housed old intercity diesel trains, class 225 from another train operator, LNER (London North Eastern Railway), trains which also did not have any aftertreatment. Like Newton Heath, Heaton is a large railway depot, 200 m in length and with 7 roads, has a large capacity to maintain a high volume of trains, with a potential 10-15 DMUs and 2 intercity 225 trains possible, to be maintained at the same time, with the engine running. This indicates that the geometry of the depot and the number of trains have an effect on the air quality and supports research question 4 which investigates the parameters affecting indoor air quality in a railway depot.

Table 5.3 Seasonal variations in indoor, ground-concentration NO_2 concentrations in the main shed of the Heaton railway depot

Season	Seasonal NO_2 concentration average (µg m^{-3})	Average ambient temperature[1] (°C)
Spring 2018	-	-
Summer 2018	90	15.5
Autumn 2018	123	10.0
Winter 2018	193	5.2
Spring 2019	-	7.9

[1] Newcastle Airport weather station (Carslaw, 2022)

5.3.3 Newton Heath Railway depot, Manchester

The concentration data from the NO_2 diffusion tubes per season at the Newton Heath railway depot is presented in Table 5.4 with weather data obtained from the WorldMet R package (Carslaw, 2022). In contrast to the Neville Hill repair shed data, the coldest ambient temperature corresponds to the highest seasonal NO_2 concentration. During winter 2018, the highest seasonal NO_2 was observed in the main shed at Newton Heath. The typical NO_2 concentrations are higher than those observed in the repair shed of Neville Hill and this can be attributed to the larger dimensions (200 m) of the Newton Heath depot with almost double the length of the Neville Hill repair shed (100 m). As with Heaton, the change in NO_2 concentrations with a large shed volume, indicates that the geometry of the depot and the types of trains, has an effect on air quality and supports research question 4 which investigates the factors affecting indoor air quality in a railway depot.

Table 5.4 Seasonal variations in indoor, ground-concentration NO_2 concentrations in the main shed of the Newton Heath depot

Season	Seasonal NO_2 concentration average (µg m^{-3})	Average ambient temperature[1] (°C)
Spring 2018	-	-
Summer 2018	-	-
Autumn 2018	61	10.6
Winter 2018	79	6.0
Spring 2019	70	9.5

[1] Manchester Airport weather station

5.3.4 Summary of the seasonal indoor NO_2 concentration in the 4 railway depots

In summary, it can be concluded that there is some evidence that seasonal weather variations have an effect on indoor air quality, with the coldest ambient temperature corresponding to the highest indoor NO_2 concentration, within all four of the 4 railway depots assessed. Therefore in line with research question 4, seasonal variations indicatively can be determined a parameter that affects air quality.

5.4 Effect of height on the indoor NO_2 concentration and the temperature within the repair shed section of the Neville Hill railway depot

To further evaluate research question 4, the variations in indoor NO_2 concentration with height were assessed in one of the four railway depots, the repair shed of the Neville Hill railway depot, to see if this shed is well-mixed. This shed was chosen due to numerous complaints of poor indoor air quality. Relative close proximity to the University of Leeds, was also a determining factor for conducting detailed air quality measurements at this location. Further details of the experimental set-up are provided in the methodology chapter (Chapter 3). Scientific questions formulated in the beginning of this chapter to support research question 4, will be answered in this sub-section to see if there is evidence of a temperature gradient in the Neville Hill railway depot's repair shed building at 4 different heights, 1.4 m, 2.3 m, 4.3 m, 5.2 m.

The heights represent of an approximate 1 m vertical spacing. The much larger gap in height between 2.3 m and 4.3 m is attributed to a poor Tinytag data capture, at an additional measurement height of 3.2 m, which had a data capture of 57.8% and so this Tinytag data was screened out due to poor data quality.

The indoor temperature data obtained from the Tinytag devices, at 10 min intervals, were quality assured by a statistical screening criteria of the hourly mean ± 3σ i.e. 10 min temperature data points that were either above or below the hourly mean ± 3σ, were screened out. Data screening removed 0.03% data from Tinytag 1 at 5.2 m, 0.05% data from Tinytag 2 at 4.3 m, 0.05% data from Tinytag 4 at 2.3 m and 0.09% data from Tinytag 5 at 1.4 m. After quality assurance, the temperature data points were averaged to four weekly intervals (Table 5.5) to align with the same period as the diffusion tube measurements in the repair shed.

Table 5.5 Four weekly intervals used for the averaged indoor temperature data and diffusion tube measurements within the repair shed of the Neville Hill railway depot

Week	Date
1	10th Apr 18 – 08th May 18
2	31st May 18 – 28th Jun 18
3	28th Jun 18 – 26th Jul 18
4	26th Jul 18 – 23rd Aug 18
5	23rd Aug 18 – 20th Sep 18
6	20th Sep 18 – 18th Oct 18
7	18th Oct 18 – 15th Nov 18
8	15th Nov 18 – 13th Dec 18
9	13th Dec 18 – 10th Jan 19
10	10th Jan 19 – 07th Feb 19
11	07th Feb 19 – 07th Mar 19
12	07th Mar 19 – 04th Apr 19
13	04th Mar 19 – 02nd May 19

Figure 5.2 shows the four-weekly average temperatures measured in the centre of the repair shed as a function of time series and height. A consistent gradient of indoor temperatures from the top (5.2 m) to the bottom (1.6 m) was observed throughout the year, indicating evidence of a temperature gradient within the shed. The greatest gaps between different heights are in week 3 (Table 5.5), which is linked to the highest indoor temperature and strongest sunlight in the summer. In a similar way to a greenhouse, solar radiation passes through the glass

panels via visible light to heat the ground. Infra-red heat is emitted from the ground and is partially reflected back to the glass panels keeping the shed warm like in a greenhouse (Hutchinson, 2016). Figure 5.3 presents the annual diurnal variation of temperature at four different heights. A clear evidence of a positive temperature gradient is shown. The largest difference in temperature between the top and bottom layers is from 10 am to 4 pm, demonstrating a strong influence of sunlight radiation on the positive temperature gradient within the shed. This could be linked to the roof material of glass panels and the apex shaped roof geometry which create a greenhouse like effect.

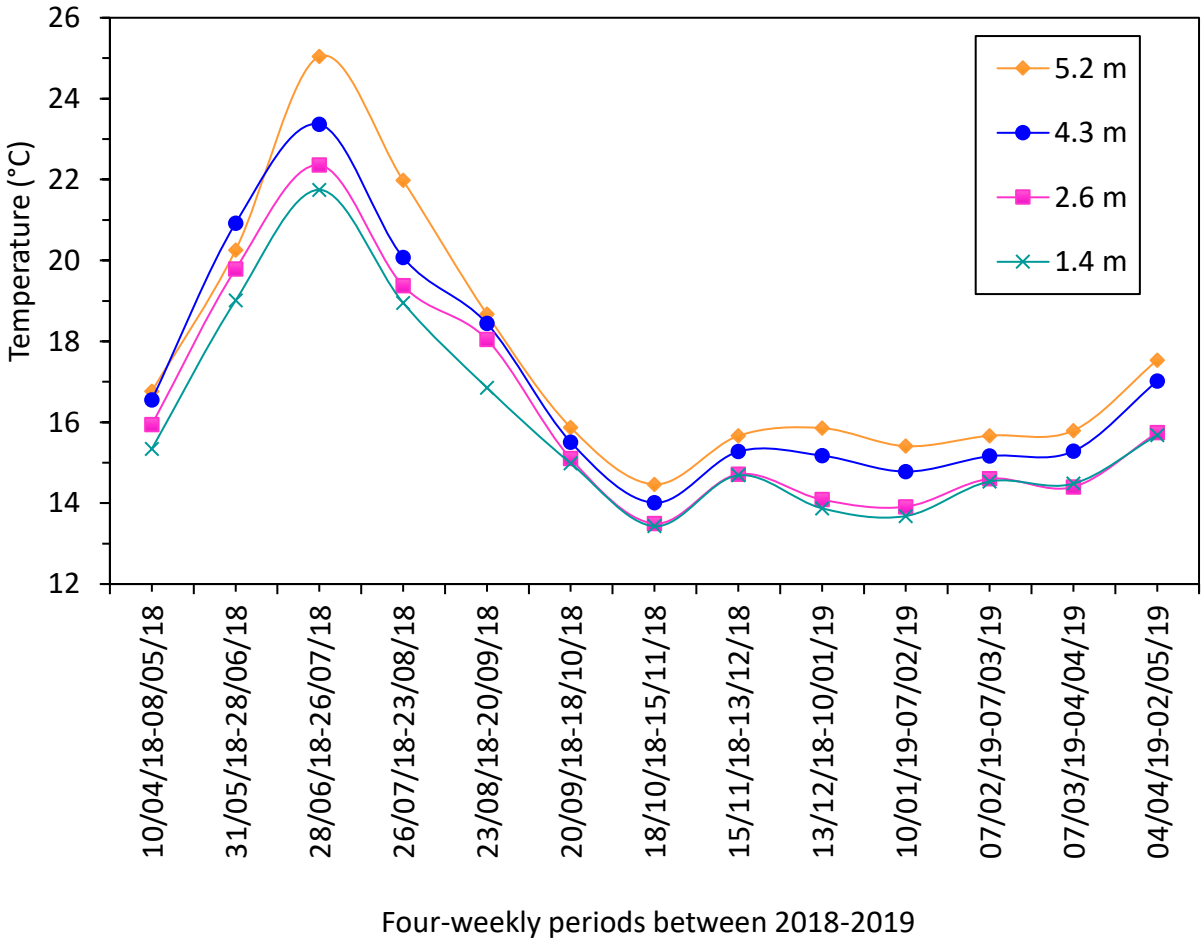


Figure 5.2 Average four weekly temperature during continuous period of monitoring from 10th April 2018 – 02nd May 2019 within the repair shed of Neville Hill railway depot

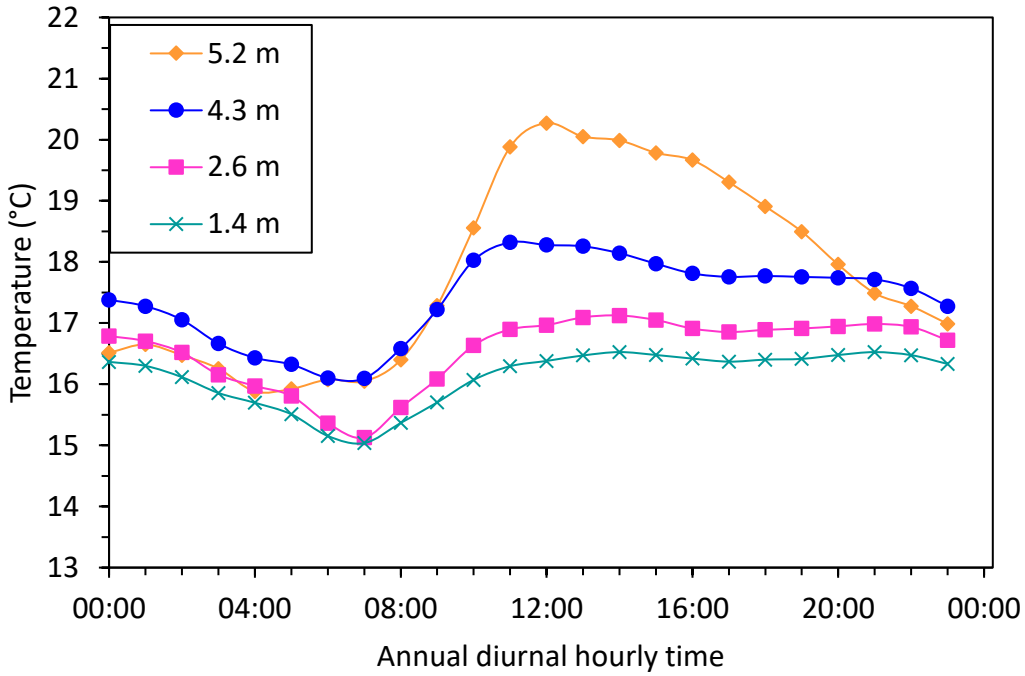


Figure 5.3 Average daily diurnal temperatures at the different heights within the repair shed on 3 Road of Neville Hill railway depot

Four-weekly average NO_2 concentrations measured by diffusion tubes are presented in Figure 5.4 as a function of time series and height, with error bars of 18%, representing the typical uncertainty of a diffusion tube . The data at 2.6 m, 4.3 m and 5.2 m were not available during weeks 9-11 and 13 due to unavailability of equipment for replacing diffusion tubes at height. In general, NO_2 concentrations increased with height as seen in Figure 5.4, with a concentration gradient of NO_2 within the repair shed. Similar phenomena were reported by the studies of Boon and Battams (Boon and Battams, 1988). This shows clear evidence of imperfect mixing and non-uniform distribution of NO_2 within the shed and is unusual behaviour as it is expected that the four-weekly NO_2 concentration values would decrease due to buoyancy effects and the indoor ventilation extraction systems dispersing the NO_2. It is hypothesised that this behaviour, involving layers of diesel fumes near roof concentration, is due to an indoor positive temperature gradient. This theory is supported by vertical temperature measurements obtained from the 4 Tinytag units at heights of 1.4 m, 2.6 m, 4.3 m and 5.2 m, as seen earlier in Figure 5.2. This answers the scientific questions which looked to evaluate if there are any depot locations which are well-mixed or not and which locations have a temperature gradient. These observations indicate that temperature and height are factors which affect air quality within a railway depot and supports research question 4.

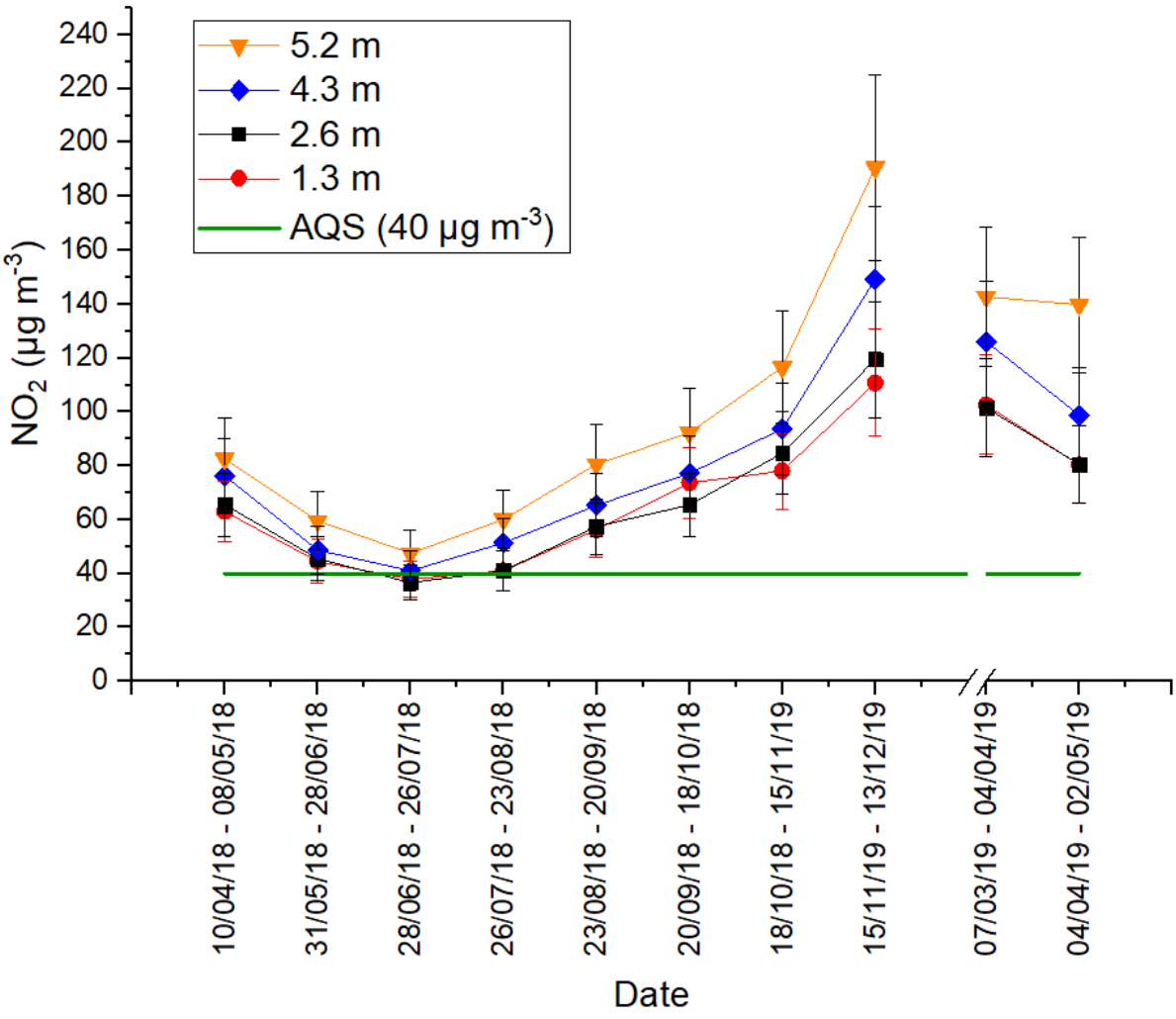


Figure 5.4 Average four-weekly NO_2 concentrations at different heights on Road 3 centre within the repair shed

Similarly, in terms of NO_2 concentration with changing height, the results in Figure 5.5 show that the NO_2 concentration gradient is proportionate to the average NO_2 concentrations. As the overall NO_2 concentration is getting higher, the concentration gradient is greater. This provided further evidence that the repair shed is not well-mixed, answering the scientific question on the well-mixed status of the shed, with a concentration gradient of NO_2 another reason for the shed not being well-mixed. In addition, for nearly all of the months (11 out of 12 months), the NO_2 monthly concentrations in the repair shed are greater numerically than the annual AQS of 40 µg m^{-3}.The error bars of Figure 5.5 represent the typical uncertainty of a diffusion tube.

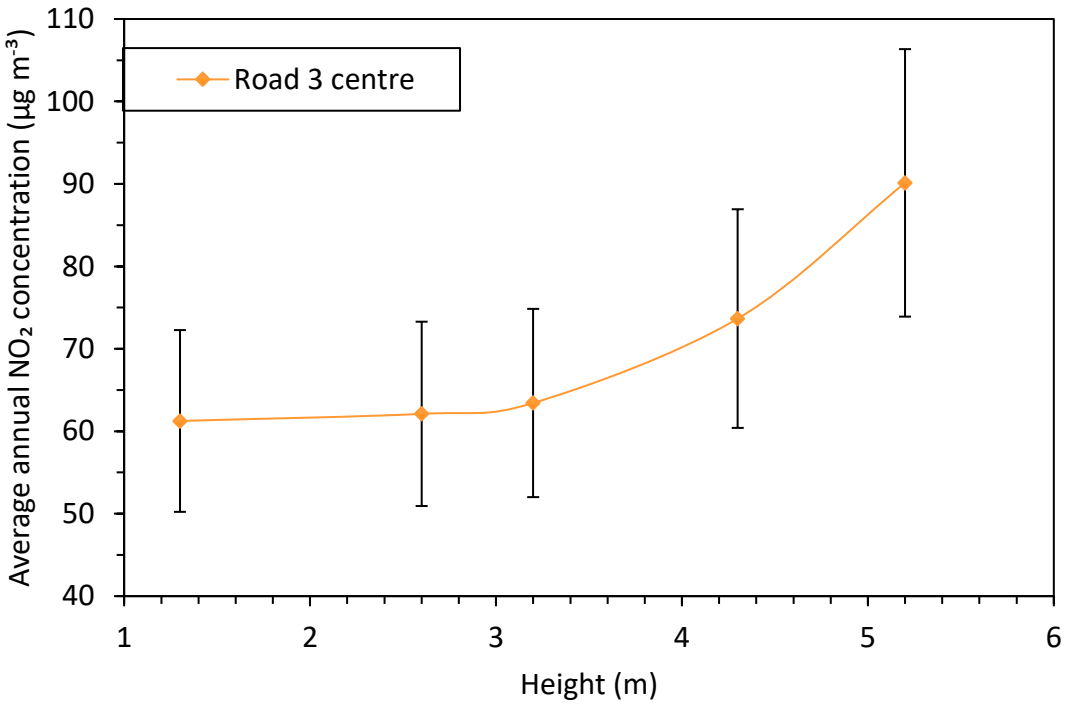


Figure 5.5 Average NO_2 concentration (µg m^{-3}) at changing height within the repair shed on Road 3

The roof extraction system consists of 20 roof fans which are used to remove diesel exhaust fumes within the repair shed. The roof fans extract the diesel fumes, and when under intense testing conditions, with multiple trains operating, the diesel fumes are removed with additional natural ventilation required via opening the railway depot's doors. The changes in temperature gradient and NO_2 should be minimal if the extract system works efficiently. The formation of the diesel plume within the shed is depicted in Figure 5.6. It shows a temporary layer of diesel fumes near roof concentration at about 3.9 m from ground concentration. This is determined by first calculating the plume rise height as calculated using the Davidson-Bryant formula under stable conditions:

$$\Delta H = SD \left(\frac{v_s}{u}\right)^{0.25} \left(1 + \frac{\Delta T_s}{T_s}\right) \quad (5.1)$$

where ΔH the rise of the plume above the stack (0.27 m), SD is the inside stack diameter (0.115 m), $\mathbf{v_s}$ is the stack gas velocity (5.56 m s^{-1}). **u** wind speed in the railway depot (0.6 m s^{-1}), ΔT_s the stack gas temperature minus the indoor temperature (165 K), T_s the stack gas temperature (456 K), T = indoor temperature (291 K).

Using equation 5.1, the Davidson-Bryant formula predicts a plume rise height of 0.27 m. The plume rise height is then added to the train exhaust height of 3.6 m

measured from ground concentration to the vertical end of the exhaust pipe, using equation 5.2:

$$H_l = H_e + \Delta H \quad (5.2)$$

where H_l = Height of temporary layer from ground concentration (3.87 m), H_e = Train exhaust height form ground concentration (3.6 m) and ΔH = the rise of the plume above the stack (0.27 m). This gives the height of the temporary layer as approximately 3.9 m (EPA, 1974) as depicted in Figure 5.5.

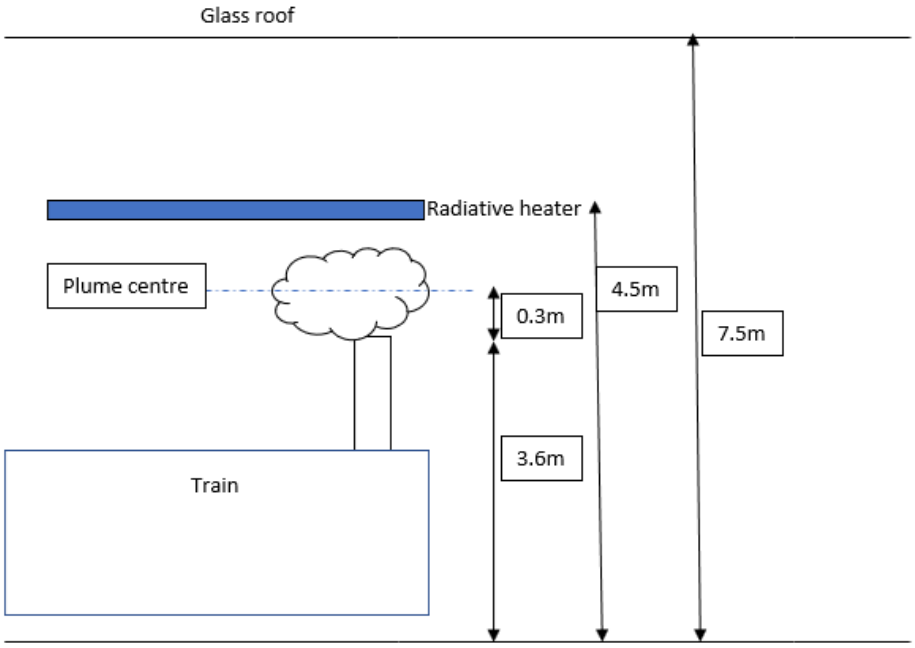


Figure 5.6 Diagram of train exhaust plume release

The NO_2 concentration data at different heights shown in Figs 5.3 and 5.4 indicates that there is a significant increase in NO_2 concentrations between 3.4 m and 4.3 m height, indicating that diesel plumes do have direct impact on the NO_2 concentrations. A similar increase in NO_2 concentrations was observed between 4.3 m and 5.2 m height, indicating accumulation of diesel exhaust above the plumes near the roof. The positive temperature gradient can be attributed to one of two possible factors; in the warmer summer months, the glass roof of the railway depot creates a heated region near the roof sampling position, which shows evidence of a larger positive temperature gradient between the midday to afternoon period as seen previously in Figure 5.3. The other factor is attributed to the radiative roof heaters which are operated in the winter months, and positioned at 4.5 m. These two factors could potentially lead to a layer of warmer air at around 3.9 m which could inhibit the mixing of air at the height which corresponds to the train exhaust pipe

(T_s = 350 – 450°C). The indoor, NO_2 concentration gradient of Figs. 5.3 and 5.4 aligns with the work of MacCarty et al. (MacCarty et al., 2020) who observed similar indoor behaviour of the pollutant of $PM_{2.5}$ within an indoor test kitchen, showing increases in both $PM_{2.5}$ and temperature with height, between the heights of 0.6 m to 2.4 m (MacCarty et al., 2020). In addition, a study by Johnson et al. (Johnson et al., 2011), showed an indoor concentration gradient of CO, within a rural, indoor, Indian kitchen environment and is another area of similarity, as this study.

Positive temperature and positive concentration gradients are indicators for incomplete mixing in the shed and non-uniformed distribution as well as poor dispersion. The results of Figure 5.2 showed as the NO_2 concentrations increased with height, the indoor temperature also increased with height. This provides evidences to answer the second and third scientific questions of the presence of temperature gradients within one of the railway depots. NO_2 concentrations at 1.3 m are the most important as they are directly linked to personal exposures. Though the values at 1.3 m were the lowest, NO_2 at height could be acting as a temporary reservoir which could subsequently transfer pollutants to ground level and thus increase the risk of personal exposure.

This sub-section has also answered the fourth scientific question (S4) which sought to find out if the main sheds in the railway depots are well-mixed. The poor mixing in the repair shed of the Neville Hill railway depot instead suggests the contrary, in that the main shed of the Neville Hill railway depot is not well-mixed. Further evidence of poor mixing is also seen at the other 3 railway depots of Allerton, Heaton and Newton Heath, as discussed earlier in section 5.3, with the diffusion tube measurements at changing height showing evidence of a concentration gradient indicating that these sheds are also not well-mixed.

This study has expanded on MacCarty's work and found similar trends in indoor temperature gradients within a non-test environment in the UK rail sector. There is also alignment with similar studies such as that of Boon and Battams, who observed increasing temperature with height within indoor environments with poor air mixing (Boon and Battams, 1988).

5.5 Evaluating the hypothesis of well-mixed behaviour in the repair shed of the Neville Hill railway depot

The purpose of this sub-section is to evaluate the well-mixed behaviour in the repair shed of Neville Hill as noted in sub-section 5.4. This is to support research question 4, by evaluating air quality parameters:

R4: What type of parameters affect the air quality of UK railway depots and train stations where diesel trains are in operation?

Previous estimations of the air extraction rate by an external consultant, equivalent to 6 ACH (air changer per hour) at 222932 m^3 h^{-1} rely on the assumption that the repair shed is well-mixed. If the repair shed, is well-mixed, then the pollutant concentration in the repair shed should be the same at all positions, and the indoor temperature should not increase with height. Conversely, if the repair shed is not well-mixed, then variations in pollutant concentration will occur within the shed and the indoor temperature will increase with height.

The importance of determining whether the repair shed is well-mixed or not, is key, as it determines how accurate the estimations of the air extraction rate conducted by the external contractor are. In a well-mixed repair shed, the estimated extraction rate of 6 ACH is correct for the repair shed air extraction rate. However, if the repair shed, if not well-mixed, the estimated air estimate rate of 6 ACH is not valid, and could potentially be much lower than this estimated value.

A hypothesis has been developed to test the well-mixed nature in the repair shed in the Neville Hill railway depot and is:

H1. The repair shed in the Neville Hill railway depot is a well-mixed shed.

In this sub-section, a time variant box model (Equation 5.3) developed by MacCarty et al. at steady state conditions, was used to evaluate this hypothesis. MacCarty et al. developed a time variant box model from first principles, at steady state conditions, for an indoor cookstove within a simulated kitchen, to replicate conditions in indoor cooking conditions in rural Nepal (MacCarty et al., 2020). The parameters of Equation 5.3, were adjusted to reflect the conditions of the indoor railway depot environment which have been provided in Table 5.6. The box model was used in this sub-section to assess the well-mixed hypothesis of the indoor NO_2 concentrations in Neville Hill railway depot's repair shed. This was done on a 1 min

timescale for an 8 h period covering the period of 07:30 and 15:30 of a typical day of train activity. The parameters used in the box model are provided in Table 5.6.

$$[NO_2]_{t+1} = [NO_2]_t + \frac{1000\ f\ q_{NO_2}}{V} + \frac{\propto([NO_2]_b - [NO_2]_{t,})}{60} \quad (5.3)$$

where $[NO_2]_{t+1}$ is the concentration of NO_2 introduced at a constant rate into a fixed volume at time t+1, *V* is the volume of the shed in m^3, q_{NO_2} is the source emission rate of NO_2 in mg min^{-1}, f is a dimensionless parameter indicating ratio of emissions that make it into the room due to effectiveness of chimney in the MacCarty et al. study where f=1 means no chimney is present, 0 means chimney totally removes emissions, $\propto$ is the air exchange rate in h^{-1}, $[NO_2]_b$ is the background concentration of NO_2 , *V* is the volume of the ventilated space (L s^{-1}), $[NO_2]_t$ is the concentration of NO_2 introduced at a constant rate into a ventilation space of volume at time t.

Table 5.6 Parameters for time variant box model

Parameter	
Start time	07:30
Finish time	15:30
Time interval (min)	3
t (min)	0 – 480
q_{NO_2} (mg min^{-1})	100.86
f	1
$\propto$	6
V (m^3)	27200
$[NO_2]_b$ (µg m^{-3})	29.07

A number of scientific questions have also been formulated to determine the suitability of the box model in line with research question 4:

SQ6. What assumptions underpin the box model?

SQ7. Is the concentration of NO_2 in the repair shed constant at all positions inside of the shed?

SQ8. Does the box model accurately predict the indoor NO_2 concentration in the repair shed at ground level?

5.5.1 Evaluation of the scientific questions

5.5.1.1 What assumptions underpin the box model?

The box model is a single zone model and assumes well mixed behaviour. It assumes that a single point source is confined to a rectangular box, with one side parallel to the wind direction and that the emission rate of the point source, in this case the air pollutant emission rate of NO_2 (q_{NO_2}), is constant. The emission rate was determined from an average of exhaust NO_2 concentrations within the repair shed over a time period of 07:30 to 15:30. These exhaust NO_2 concentrations, as explained previously in Chapter 3, were obtained from a chemiluminescence analyser connected to the exhaust of the DMUs, using a PEMS (portable emission monitoring system) for approximately a 15-20 min period per DMU. Using train activity data, an estimate was determined for the average emission rate over an 8 h period, to be incorporated into the box model. The most important aspect of the box model is that it assumes that the pollutant concentration is uniform within the entire box, in this case NO_2, which underpins the well-mixed assumption.

5.5.1.2 Is the concentration of NO_2 in the repair shed constant at all positions inside of the shed?

Using Equation 5.3 and the parameters of Table 5.6, the indoor NO_2 concentration was predicted for the repair shed of Neville Hill, as seen in Figure 5.7. The variation in NO_2 concentration with time, indicates that the shed is not well-mixed. This proves that the hypothesis H1 is false. Therefore, if the shed is not well-mixed, then it can be concluded that the NO_2 concentrations inside the repair shed are not constant at all points within the shed.

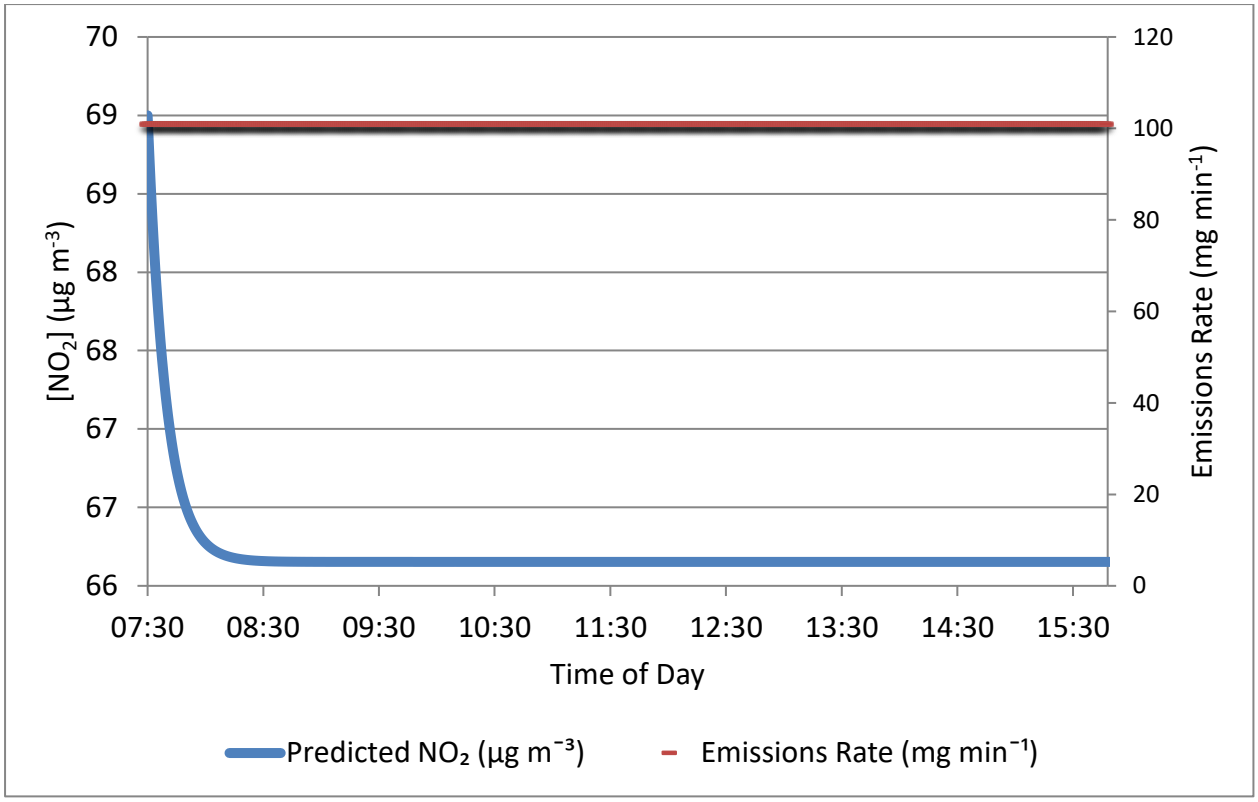


Figure 5.7 Time variant box model of indoor NO_2 in the repair shed of the Neville Hill railway depot

5.5.1.3 Does the box model accurately predict the indoor concentration in the repair shed at ground level?

The box model predictions of indoor NO_2 concentration were validated against typical transient NO_2 concentration data at ground level, during the time period of 07:30 to 15:30, as seen in Figure 5.8. These concentrations were obtained from a NO_x chemiluminescence analyser recording the NO, NO_2 and NO_x concentrations in the middle of the repair shed on a 3 min interval. It must be noted that these transient NO_2 concentrations were not conducted at the same time as NO_2 exhaust concentrations used for the emission rate. In contrast to the box model prediction of NO_2 concentration of Figure 5.7, there are significant changes in the NO_2 concentration with time and therefore the box model is not an accurate method for predicting the indoor NO_2 concentration in the repair shed at Neville Hill. This indicates complex mixing behaviour within the repair shed, and parameters such as seasonal weather variations (sub-section 5.3) and indoor temperature (sub-section 5.4) as noted earlier affect indoor air quality; answering research question 4.

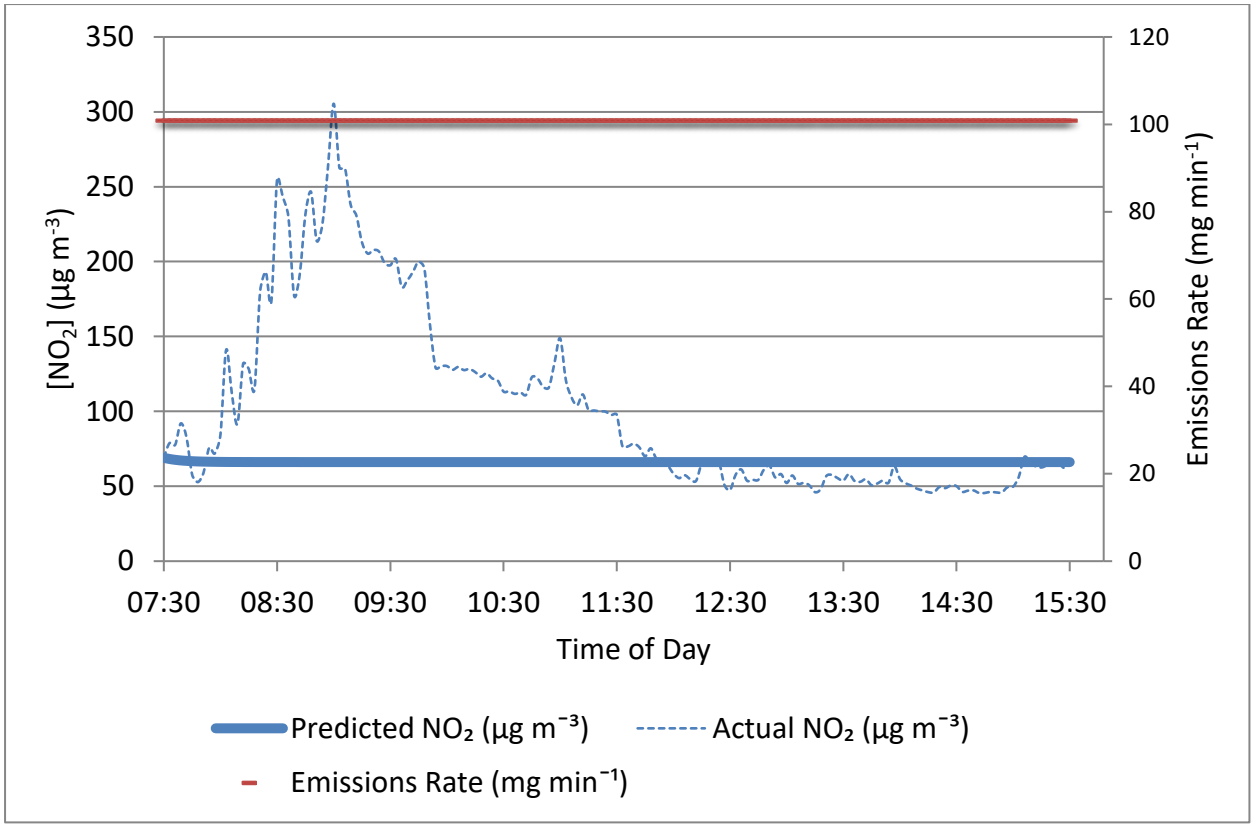


Figure 5.8 Comparison of the time variant box model of indoor NO_2 in the repair shed of Neville Hill against typical measurement data for indoor NO_2 concentration at steady state

The box model of Figure 5.8 has assumed a constant emission rate for NO_2, which assumes steady state conditions. Using a time variant hourly emission rate, as in Figure 5.10, shows that there is a time lag between the high emissions and peaks in the measured NO_2. This could be attributed to slow mixing from the emission height to the ground level where the measurements are being conducted. This would be consistent with the idea that the vertical exchange is slow.

Expanding the box model, using a time variant hourly emission rate, as seen in Figure 5.9 highlights the complex mixing behaviour within the repair shed, with the predicted NO_2 significantly higher than the actual NO_2 during periods which the DMUs were under test. This provides further indicative evidence that the repair shed is not well-mixed. Averaging these NO_2 concentrations over a typical 8 h work period in line with UK WELs, as seen in Figure 5.10, the predicted NO_2 was below the actual NO_2 within the repair shed over a typical Mon-Fri working week (07:30-15:30). This could be due to the overestimation of the ACH in the repair shed, at 6 ACH, which the predicted NO_2 was determined from.

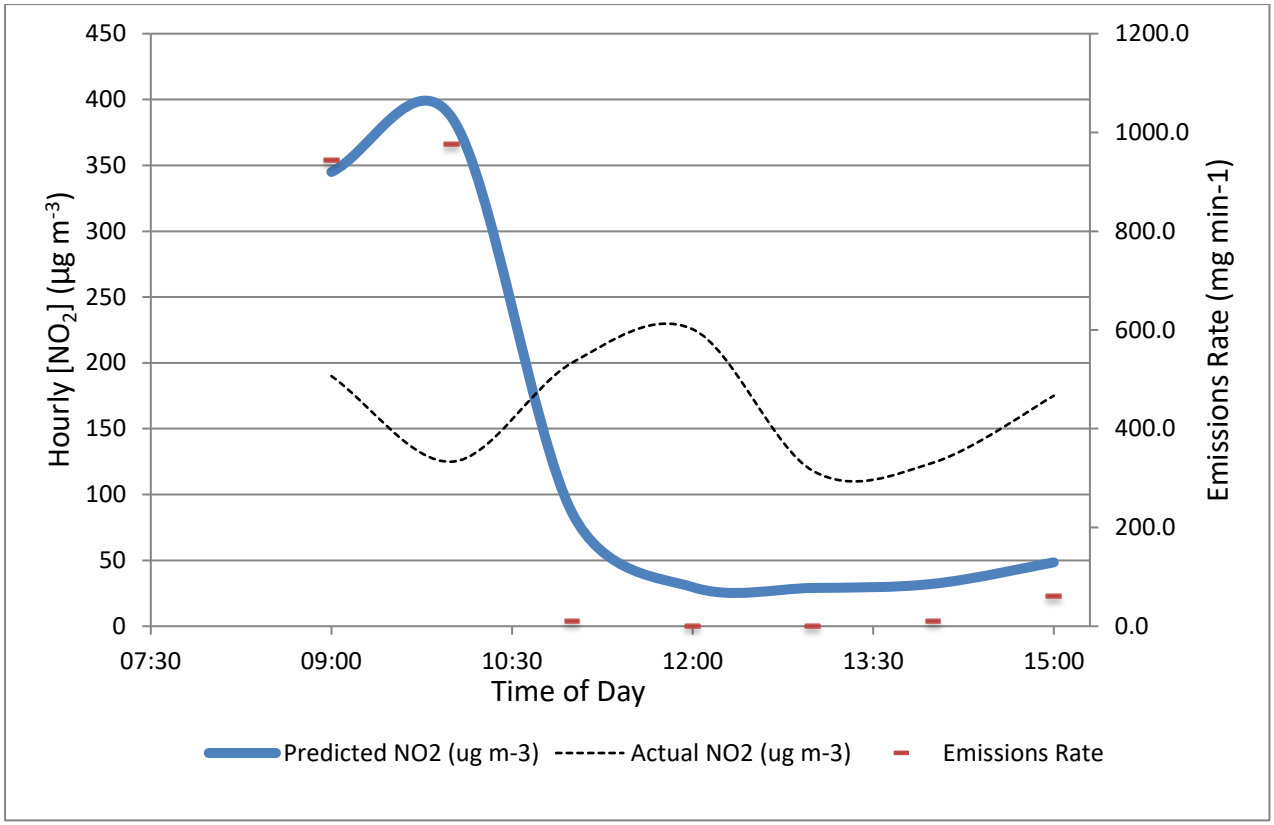


Figure 5.9 The time variant box model of indoor NO_2 in the repair shed of Neville Hill at unsteady state conditions

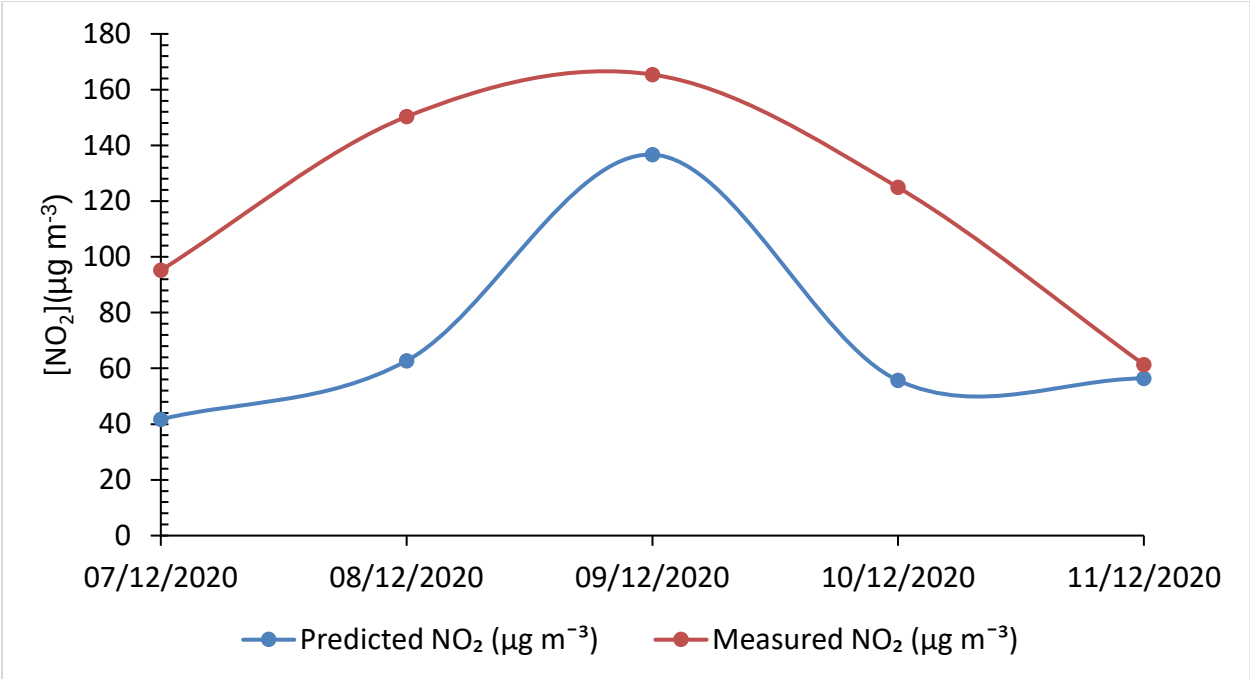


Figure 5.10 Comparison of the time variant box model of indoor NO_2 averaged over 8 h in the repair shed of Neville Hill against typical measurement data for indoor NO_2 concentration at unsteady state conditions

5.6 Evidence of a temperature gradient in other railway depots

At the Allerton, Newton Heath and Heaton railway depots, the NO_2 concentration increased with height within the main sheds of activity as seen in Figs. 5.8–5.11. This provides an indication of a positive concentration gradient in these sheds, most likely due to poor mixing of air within these respective main shed, similar of Neville Hill noted in sub-sections 5.4 & 5.5. In Figure 5.11, the concentration gradient in the main shed of the Allerton railway depot, is seen with increases in NO_2 concentration with height from 1.6 m to 4.5 m. In similar way, in the main shed of the Heaton railway depot as seen in Figure 5.12, increases in NO_2 concentration with height were found from 1.6 m to 5 m. Figure 5.13 shows the concentration gradient in the main shed of the Newton Heath depot, with increases in NO_2 concentration with height from 1.6 m to 5.6 m. The much lower NO_2 concentrations at each height at the Allerton railway depot, as noted in sub-section 5.3.1 is attributed to small quantity of diesel trains at this particular depot, in contrast to the other railway depots which have much higher numbers of diesel trains.

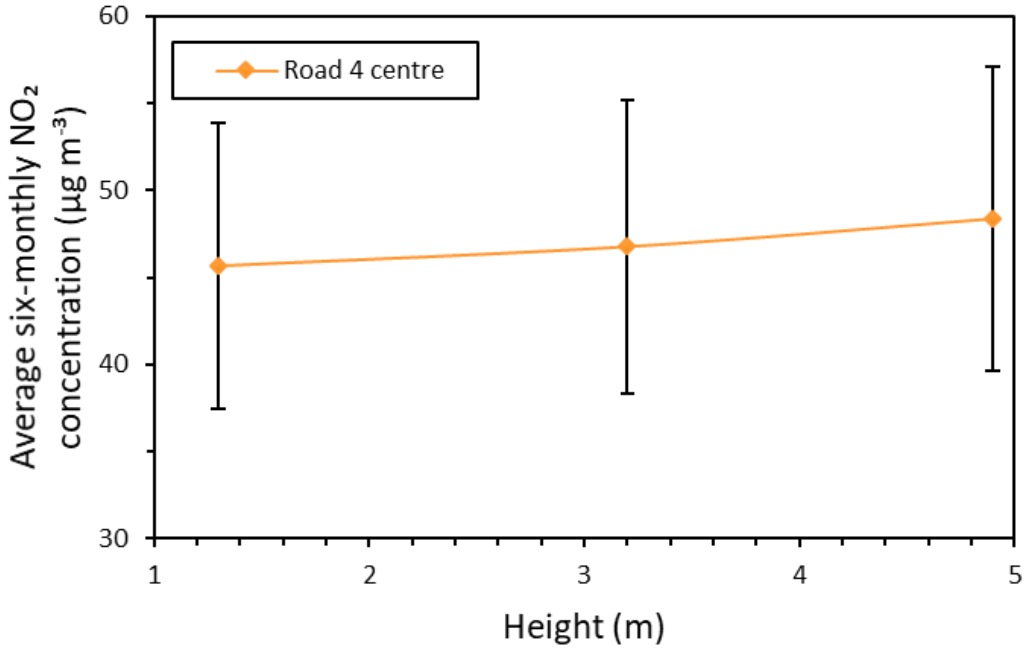


Figure 5.11 Average NO_2 concentration (µg m^{-3}) at changing height within the main shed of the Allerton railway depot on Road 4

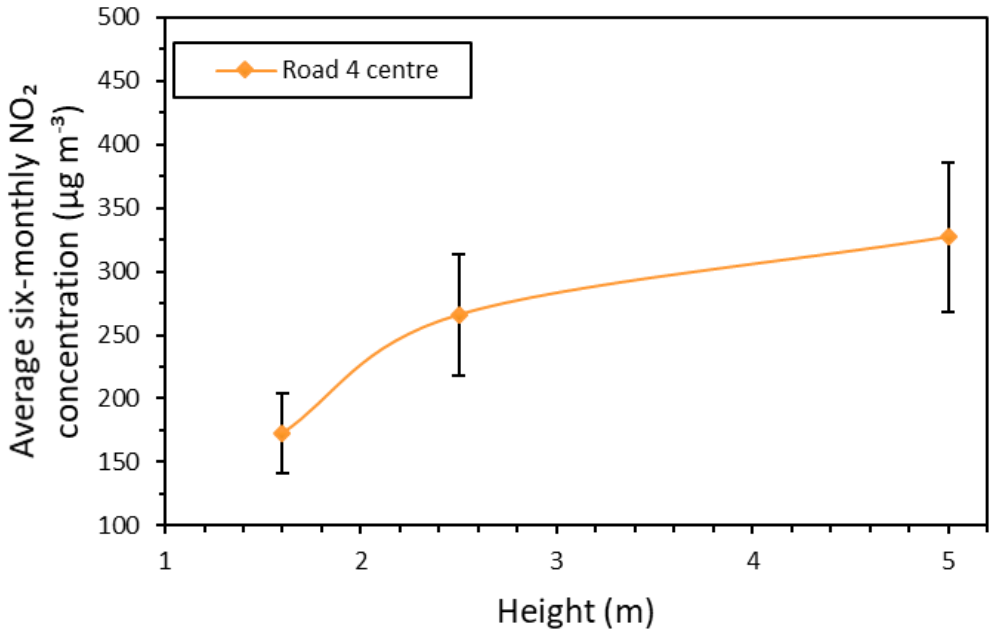


Figure 5.12 Average NO_2 concentration (µg m^{-3}) at changing height within the main shed of the Heaton railway depot on Road 4

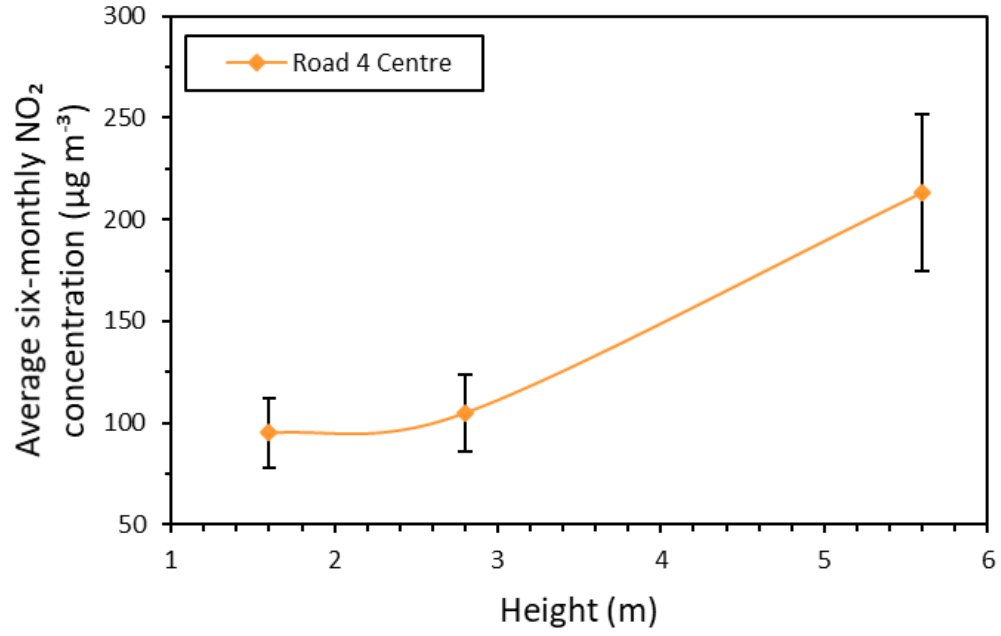


Figure 5.13 Average NO_2 concentration (µg m^{-3}) at changing height within the main shed of the Newton Heath railway depot on Road 4

5.7 Comparison of the annualised indoor NO_2 railway depot concentrations against the annual UK AQS and WHO (World Health Organisation) guideline for NO_2

Each NO_2 diffusion tube concentration at each of the railway depots was annualised as per the LAQM TG22 guidance, since the data capture covered less than 9 months in a calendar year (LAQM, 2022b). This annualisation was conducted first for the year of 2018 and then separately for year of 2019. Annualisation, involves using data from 2 or more AURN (Automatic Urban and Rural Monitoring Network) background sites, to correct NO_2 diffusion tube data by an annualisation factor, when there is less than 9 months of diffusion tube data in a calendar year. However, there must be a minimum of 3 months of diffusion tube data otherwise annualisation cannot be conducted. Following annualisation, a relative bias correction is applied to the annualised NO_2 concentration for each diffusion tube. In this study, a national bias correction factor of 0.89 was used for this calculation, based on a 50% TEA (Triethanolamine)/Acetone diffusion tube from the supplier Gradko, which was obtained from the LAQM national bias factor database, using national bias adjustment factors for 2018 and 2019 (LAQM, 2021b). Further details on this process is provided in the methodology chapter (Chapter 3).

5.7.1 Allerton railway depot

For 2018, diffusion tube data from 19th Oct 2018 – 11th Jan 2019 was utilised, with annualisation applied by using continuous background NO_2 data from 2 AURN sites between 01st Jan 2018 and 11th Jan 2019 to correct the diffusion tube NO_2 concentrations. The AURN sites were selected based on the nearest sites to the Allerton railway depot (Wirral and Wigan Centre). Details of the annualised and bias corrected NO_2 diffusion data are provided in Table 5.7. Following annualisation and bias adjustment, the average concentration in the main shed at Allerton was determined to be 29 µg m^{-3} in 2018 and 36 µg m^{-3} in 2019. This doesn't exceed the UK's AQS for NO_2 of 40 µg m^{-3} (DEFRA). It is however above the WHO air quality guideline value of 10 µg m^{-3} NO_2 annually (WHO, 2021a). Both the UK AQS and WHO do not have any legal status within railway depots, which are instead governed by WELs (workplace exposure limits) on 15 min (1910 µg m^{-3} NO_2) and 8 h (955 µg m^{-3} NO_2) time weighted average (TWA) with much higher NO_2 thresholds. However, it is a useful comparative benchmark, to see how the railway depots compare

against the limits such as UK AQS and WHO guidelines designed for outdoor spaces. Liverpool City Council have a non-automatic monitoring site relatively close to the Allerton railway depot, on Speke Rd (site: S11), where the annual NO_2 was noted as 44 µg m^{-3} (LICC, 2020a; Google, 2022g). This is much higher than the indoor annual NO_2 observed at Allerton.

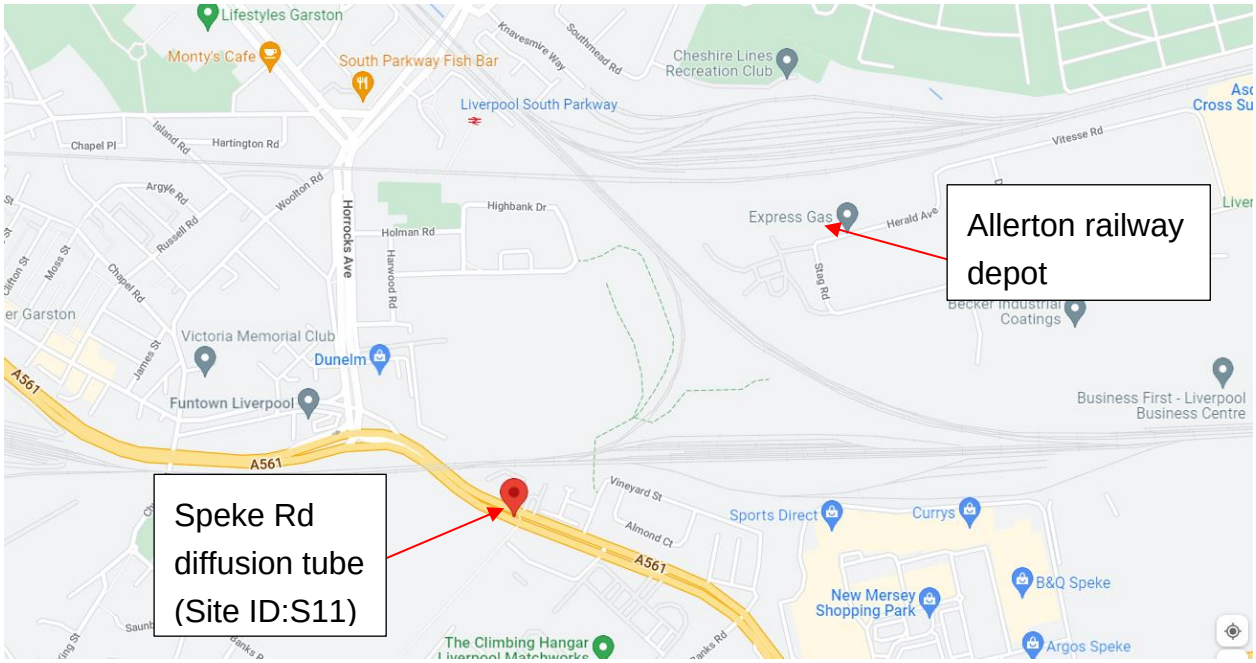


Figure 5.14 Nearest Liverpool City Council non-automatic monitoring site in relation to the Allerton railway depot (Google, 2022g; LICC, 2020b)

Table 5.7 Annualised and relative bias adjusted indoor NO_2 concentration data for the Allerton depot main shed

	Time Weighted Annual Mean (µg m^{-3})	
Diffusion Tube ID	**2018 Bias Adjusted (0.89) and Annualised**	**2019 Bias Adjusted (0.89) and Annualised**
Road 1 Centre	29	29
Road 3 Centre	-	31
Road 4 Centre	29	38
Road 5 Centre	28	42
Allerton End Road 1	26	27
Allerton End Road 3	27	-
Allerton End Road 4	30	41
Allerton End Road 5	30	-
Hunts Cross End Road 1	33	30
Hunts Cross End Road 3	36	32
Hunts Cross End Road 4	31	40
Hunts Cross End Road 5	23	42
Road 4 Centre 3.2m	29	40

	Time Weighted Annual Mean (µg m^{-3})	
Diffusion Tube ID	**2018 Bias Adjusted (0.89) and Annualised**	**2019 Bias Adjusted (0.89) and Annualised**
Road 4 Centre 4.9m	28	43
Average at ground level of 1.6m	29	36

Using the data from Table 5.7, an average NO_2 concentration for the main shed at Allerton depot was determined at ground level. For consistency, ground level was taken using diffusion tubes positioned at the same height, i.e. 1.6 m. The average annualised bias-adjusted NO_2 concentrations were calculated to be 29 µg m^{-3} in 2018 and 35 µg m^{-3} in 2019. Hotspots were identified within the main shed with indoor NO_2 concentrations above than UK AQS limit of 40 µg m^{-3} at both ground level on Road 5 and at a height on Road 4 (DEFRA).

5.7.2 Heaton railway depot

For 2018, diffusion tube data from 19th Oct 2018 – 11th Jan 2019 was utilised with annualisation applied by using continuous background NO_2 data from 3 AURN sites between 01st Jan 2018 and 11th Jan 2019 to correct the diffusion tube NO_2 concentrations. The AURN sites were selected based on the nearest sites to the Heaton railway depot (Newcastle Centre, Sunderland Silksworth and Hartlepool). Details of the annualised and bias corrected NO_2 diffusion concentrations are provided in Table 5.8. Following annualisation and relative bias adjustment, the average concentration in the main shed of Heaton was determined to be 99 µg m^{-3} in 2018. This exceeds the UK AQS of 40 µg m^{-3}. It is also above the WHO air quality guideline value of 10 µg m^{-3} NO_2 annually (WHO, 2021a).

Newcastle City Council have a non-automatic monitoring site relatively close to the Heaton railway depot, on Coast Rd. (Site ID:DT84, XY:428143 566886) , where the annual NO_2 was noted as 45 µg m^{-3}. This is much lower than the observed the indoor annual NO_2 at Heaton's main shed of 99 µg m^{-3} (NCC, 2019b). Possible reasons for this could include, poor mixing of air within the main shed at Heaton, higher emissions rate in a confined space, due to diesel DMUs without aftertreatment technology and also the DMU are tested for longer periods, than in the case of the outdoor site where vehicles would in most cases just be transiting past the diffusion tube location on Coast Rd (DT84).

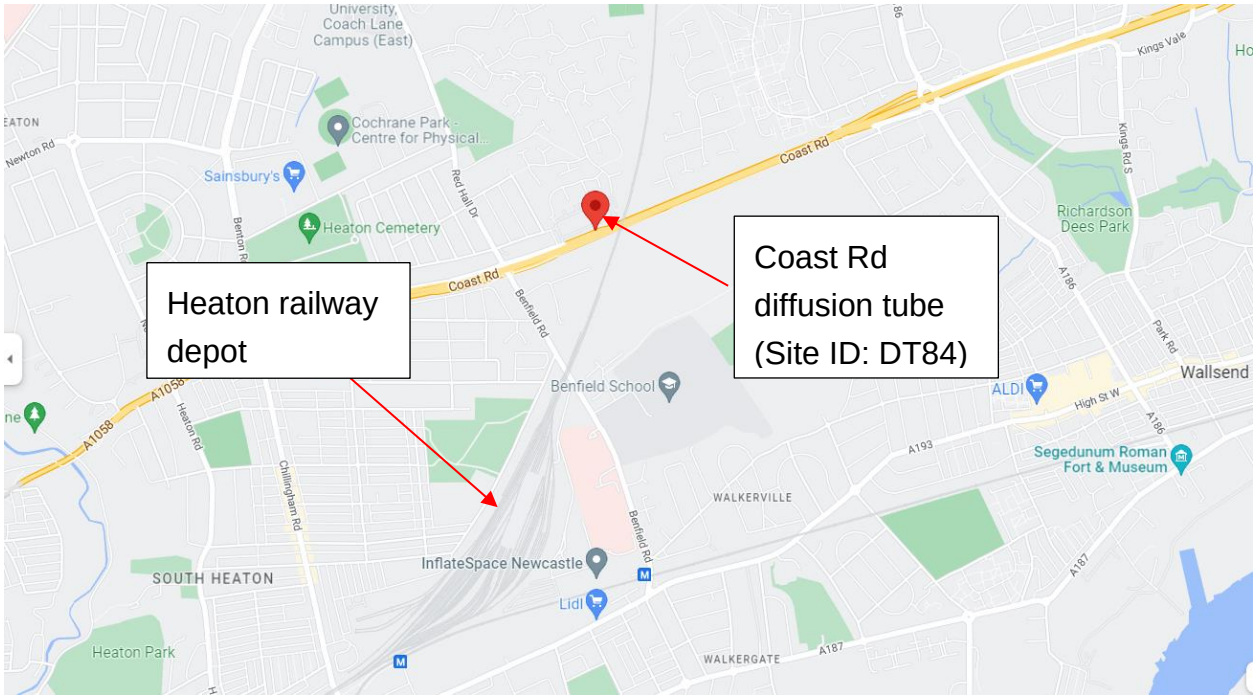


Figure 5.15 Nearest Newcastle City Council non-automatic monitoring site in relation to the Heaton railway depot (Google, 2022c; NCC, 2019a)

Table 5.8 Annualised and relative bias adjusted indoor NO_2 concentration data for the Heaton depot main shed

Diffusion Tube ID	2018 Time Weighted Annual Mean (µg m^{-3})
Road 1 Centre	164
Road 1 North	150
Road 2 North	126
Road 3 North	136
Road 4 North	132
Road 5 North	95
Road 6 Centre	69
Road 7 Centre	70
Road 7 South	84
Road 6 South	83
Road 5 South	72
Road 4 South	61
Road 3 South	69
Road 2 South	86
Road 1 South	82
Road 4 Centre 5m	269
Road 4 Centre 2.5m	208
Road 4 Centre 1.6m	105
Average at ground level of 1.6 m	99

Using the data from Table 5.8, an average NO_2 concentration for the main shed at Allerton depot was determined at ground level i.e. 1.6 m. For consistency, this was taken using diffusion tubes positioned at the same height, i.e. 1.6 m. The average annualised relative bias-adjusted NO_2 concentration was calculated to be 99 µg m^{-3} in 2018. After annualisation and bias adjustment, it was interesting to note, that at every single diffusion tube had a concentration greater than the UK AQS for NO_2 of 40 µg m^{-3} NO_2 annually.

5.7.3 Neville Hill railway depot

For 2018, diffusion tube data from 19th Oct 2018 – 11th Jan 2019 with annualisation applied by using continuous background NO_2 data from 2 AURN sites between 01st Jan 2018 and 11th Jan 2019 to correct the diffusion tube NO_2 concentrations. The AURN sites were selected based on the nearest sites to the Neville Hill railway depot (Leeds Centre and Barnsley). Details of the annualised and relative bias corrected NO_2 diffusion data are provided in Table 5.9.

Table 5.9 Annualised time weighted annual NO_2 concentrations for the Neville Hill railway depot

Diffusion Tube ID	2018 Time Weighted Annual Mean (µg m^{-3})	2019 Time Weighted Annual Mean (µg m^{-3})
Road 1 East	52	72
Road 1 Centre	54	74
Road 1 West	56	83
Road 2 East	54	77
Road 2 Centre	56	67
Road 2 West	55	56
Road 3 East	50	79
Road 3 West	64	81
Road 4 East	55	80
Road 4 West	54	75
Road 5 East	56	81
Road 5 Centre	70	109
Road 5 West	58	72
Road 3 Centre (5.2m)	91	-
Road 3 Centre (4.3m)	75	-
Road 3 Centre (3.2m)	65	-
Road 3 Centre (2.6m)	64	-
Road 3 Centre (1.3m)	63	-
Average at ground level of 1.6 m	57	77

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Following annualisation and bias adjustment, the average concentration in the repair shed at Neville Hill was determined to be 57 µg m^{-3} in 2018 and 77 µg m^{-3} in 2019. This exceeds the UK's AQS of 40 µg m^{-3} and the WHO air quality guideline value of 10 µg m^{-3} NO_2 annually. Nearby to the Neville Hill railway depot, on Osmondthorpe lane, there is a non-automatic monitoring site operated by Leeds City Council (site: D383). At this location, the annual NO_2 in 2018 was recorded as 43 µg m^{-3} (LCC, 2019b; Google, 2022d). This is below that observed within Neville Hill's repair shed in 2018.

Figure 5.16 Nearest Leeds City Council non-automatic monitoring site in relation to the Neville Hill railway depot (LCC, 2019b; Google, 2022d)

Leeds City Council also have an automatic monitoring site reasonably close to the Neville Hill railway depot at Temple Newsam In 2018, the annual NO_2 concentration at Temple Newsam was recorded as 16 µg m^{-3} with the monthly concentration varying between 12 and 20 µg m^{-3} as seen in Table 5.10 (LCC, 2019c). In comparison, the NO_2 concentrations observed in the repair shed of the Neville Hill railway depot varied between 33 and 120 µg m^{-3} over the 52 weeks with much higher levels than the Temple Newsam roadside location. It is expected that within a railway depot, the NO_2 concentrations, would be much higher than that of a roadside, due to the enclosed nature of railway depot, which leads to accumulating of NO_2 within a confined space. The changes in concentration with height noted within this chapter for the railway depots, in particular sub-section 5.5 for the repair shed of the Neville Hill railway depot, means that extraction of the NO_2 generated within the shed from the

DMU exhausts, is likely to be inhibited due to poor mixing of air, arising from limited natural ventilation and poorly positioned roof-mounted mechanical ventilation systems. The measured indoor wind speed was 0.7 ms^{-1}. Consequently, with such poor mixing, more NO_2 is expected within indoor confined spaces such as the Neville Hill railway depots in comparison to the outdoor roadsides which are likely to have greater wind speeds (3.2 – 4.7 ms^{-1} at Leeds Bradford Airport in 2018, the nearest wind speed site to Temple Newsam), than that seen at Neville Hill (OpenAir, 2018).

Table 5.10 Monthly NO_2 concentrations at Temple Newsam in 2018 obtained from LCC (LCC, 2019c)

Temple Newsam 2018	
Month	**Monthly NO_2 (µg m^{-3})**
Jan	20
Feb	19
Mar	17
Apr	15
May	14
Jun	12
Jul	12
Aug	14
Sep	15
Oct	17
Nov	17
Dec	20
Annual average	**16**

The RSSB, in more detailed modelling as part of their T1190 report, looked at the effect of pollution for the entire Neville Hill railway depot site in 2020, which includes Northern Rail's repair shed as well as other sheds on the site (Northern Rail's service shed, Northern Rail's refuelling shed, East Midlands Main Shed and East Midlands Service Shed) (RSSB, 2021a). They found that the highest emission source of NO_x originated from a gas boiler on the site for heating, in the Eastern part of the depot as seen in Figure 5.17. From Figure 5.17, the modelled annual NO_2 for the repair shed was estimated between 51 – 63 µg m^{-3}.

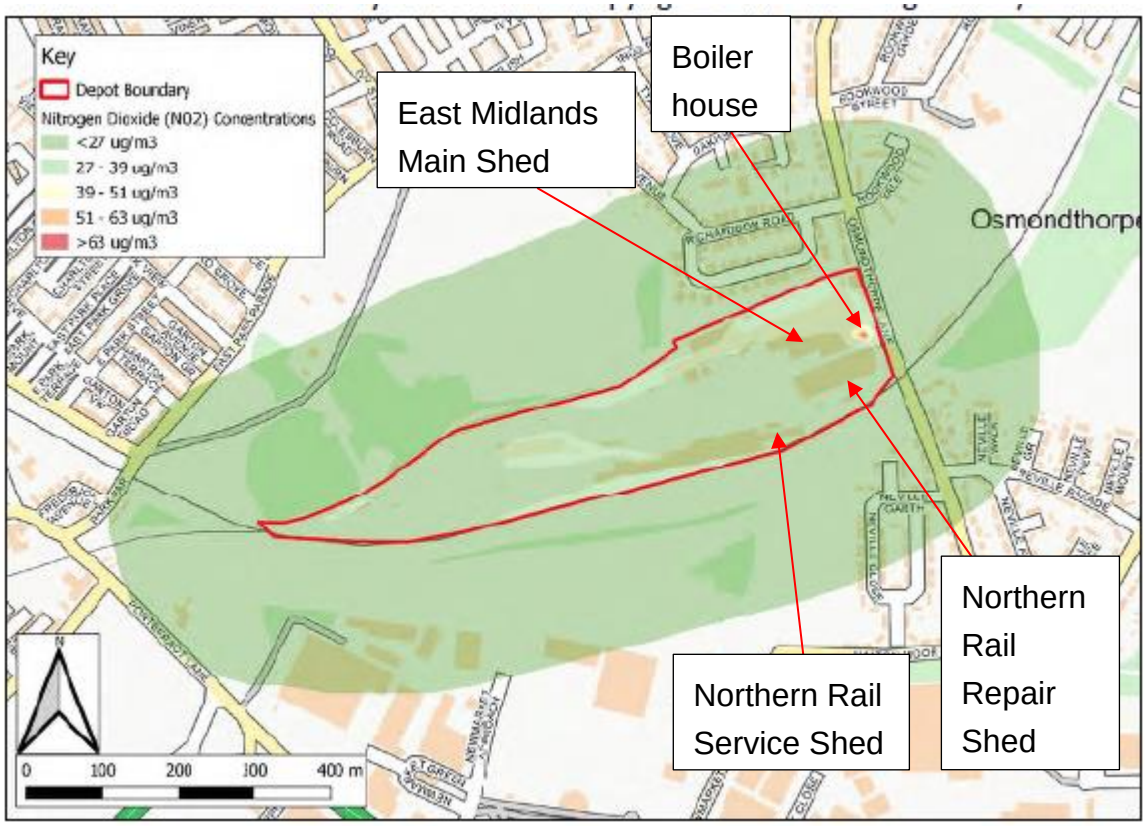


Figure 5.17 Total modelled annual NO_2 concentration at the Neville Hill railway depot (reproduced from RSSB) (RSSB, 2021a)

The difference in years between this modelled annual NO_2 data for 2020, and the measured annualised NO_2 of this study for 2018 and 2019, makes it difficult to directly compare. However, numerically the 2018 measured annualised NO_2 of 57 µg m^{-3} is within the modelled annual NO_2 range of 51 – 63 µg m^{-3}. The 2019 measured annualised of 77 µg m^{-3} is above the modelled annual NO_2 range of 51 – 63 µg m^{-3}.

5.7.4 Newton Heath Railway depot

For 2018, diffusion tube data from 19th Oct 2018 – 11th Jan 2019 was utilised and correcting these NO_2 concentrations by using continuous background NO_2 data from 2 AURN sites between 01st Jan 2018 and 11th Jan 2019. The AURN sites were selected based on the nearest sites to the Newton Heath railway depot (Manchester Piccadilly and Salford Eccles). Details of the annualised and bias corrected NO_2 diffusion data are provided in Table 5.11. Following annualisation and bias adjustment, the average concentration in the repair shed at Newton Heath was determined to be 48 µg m^{-3} in 2018. This exceeds the UK's AQS of 40 µg m^{-3} (DEFRA). It is also above the WHO air quality guideline value of 10 µg m^{-3} NO_2

annually (WHO, 2021a). Greater Manchester Combined Authority have a non-automatic monitoring site on Mellor St. (SiteID: OLMSNO), 0.8 mi East of Newton Heath, pictured in Figure 5.18, which had an annual NO_2 concentration of 23.7 µg m^{-3}, approximately half that of Newton Heath (CleanairGM, 2018; GMCA, 2019a; Google, 2022f).

Table 5.11 Annualised time weighted annual NO_2 concentrations for the Newton Heath railway depot

Diffusion Tube ID	**2018 Time Weighted Annual Mean (µg m^{-3})**
Road 4 Centre 5.6m	113
Road 4 Centre 2.8m	54
Road 4 Centre 1.6m	47
Road 7 Centre 1.6m	42
Road 10 Centre 1.6m	41
Road 4 Manchester End 1.6 m	55
Road 5 Manchester End 1.6m	62
Road 6 Manchester End 1.6m	62
Road 7 Manchester End 1.6m	49
Road 8 Manchester End 1.6m	54
Road 10 Manchester End 1.6m	45
Road 4 Oldham End 1.6m	31
Road 5 Oldham End 1.6m	54
Road 6 Oldham End 1.6m	48
Road 7 Oldham End 1.6m	40
Road 8 Oldham End 1.6m	40
Road 9 Oldham End 1.6m	-
Road 10 Oldham End 1.6m	43
Average at ground level	**48**

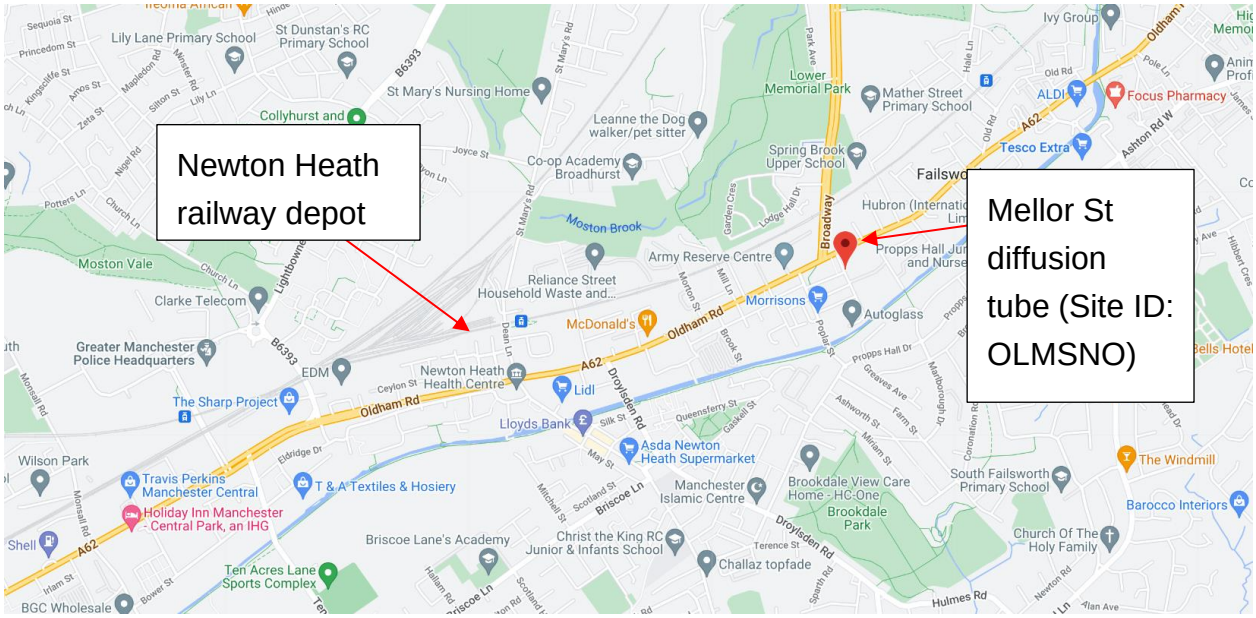


Figure 5.18 Nearest Greater Manchester non-automatic monitoring site in relation to the Newton Heath railway depot (GMCA, 2019a; Google, 2022f)

5.7.5 Summary of the 4 railway depots against UK AQS

As seen in Table 5.12, 3 of the 4 railway depots, have annualised NO_2 concentrations above the UK AQS for NO_2 of 40 µg m^{-3} annually (DEFRA). These occur within the primary sheds of activity within the railway depots of Heaton, Neville Hill and Newton Heath. These 3 railway depots, in particular, maintain and repair a significant number of diesel trains within their primary sheds, with between 10-20 individual diesel carriages housed within each of the sheds, at the respective depots. Allerton railway depot, the only location which had an annualised NO_2 concentrations below the UK AQS limit, maintains a lot of electric trains (60% of the depot capacity) with only approximately 2-5 individual diesel carriages within the main shed at this depot. All four of the railway depots, including depot, however have annualised NO_2 concentrations above the WHO air quality guideline value of 10 µg m^{-3} NO_2 annually (WHO, 2021a). As noted previously, the UK AQS and WHO values for NO_2 do not have legal status within indoor spaces such as enclosed railway depots and are designed for outdoor spaces to protect vulnerable groups such as the elderly, young children, pregnant women, etc.

Table 5.12 Comparison of the averaged four-weekly NO_2 concentrations at ground level for the 4 railway depots of this study

Railway depot	Shed	Monitoring period	2018 Average	2019 Average	UK AQS	Above the UK AQS
			NO_2 $\mu g\ m^{-3}$	NO_2 $\mu g\ m^{-3}$	NO_2 $\mu g\ m^{-3}$	
Allerton	Main Shed	6 months	29	36	40	No
Heaton	Main Shed	6 months	99	-	40	Yes
Neville Hill	Repair Shed	12 months	57	77	40	Yes
Newton Heath	Main Shed	6 months	48	-	40	Yes

5.8 Air quality in a UK rail station

5.8.1 Overview

Expanding on the previous sub-section, this sub-section assess the static NO_2 concentrations within a train station to evaluate the second part of research part of research question 4 referring to train stations:

R4: What type of parameters affect the air quality of UK railway depots and train stations where diesel trains are in operation?

A number of scientific questions have been formulated to support research question 4 and are as follows:

SQ9. How does the NO_2 indoor concentration vary with time within the Manchester Victoria train station?

SQ10. Is there any indication of a NO_2 concentration gradient within the Manchester Victoria station?

Air quality measurements of Northern Rail's Manchester Victoria station were conducted from the 08th November 2018 – 15th November, 2019 to assess research question 4 of evaluating the air quality parameters in a rail station. As outlined in the methodology chapter, the monthly, indoor NO_2 concentration was monitored using diffusion tubes at the Manchester Victoria station in Manchester for a 1 year period. The majority of the diffusion tubes were installed at height of 2.5 m, to minimise the risk of theft, with a further 4 tubes installed at a height of 2.7 m in the interconnecting platform overbridge between the station's platforms 3 & 6.

5.8.2 Evaluation of Manchester Victoria station diffusion tube data

Static air quality monitoring is an assessment method for determining the changes in air quality on a long term time scale e.g. 1 month. For this study, as outlined previously in the methodology, static monitoring of NO_2 was conducted at multiple locations in the Manchester Victoria station (full results in Appendix F); using diffusion tubes and using error bars of 18% derived from uncertainty measurements from Bush et al. (Bush et al., 2001).

In the Manchester Victoria station, the highest NO_2 concentrations, as seen in Figure 5.19 were observed in the overbridge section which interconnected several of the platforms, which had no ventilation extraction system during the period of monitoring of 2018-19. Within this particular zone, the four weekly NO_2 concentration, without bias correction, varied between 161 – 241 µg m^{-3} across the one year period of monitoring between Nov 2018 – Dec 2019. At platform level however, the four weekly NO_2 concentration varied between 43 – 65 µg m^{-3}. The geometry of the station, with the overbridge located approximately 5 m above platform, suggests that there may be indications of a concentration gradient within the overbridge, where the diffusion tubes are at height of 2.5 m within the overbridge or effectively 7.5 m above ground level. The error bars of Figure 5.19, set at 18% reflect the typical uncertainty of a diffusion tube from literature (Bush et al., 2001).

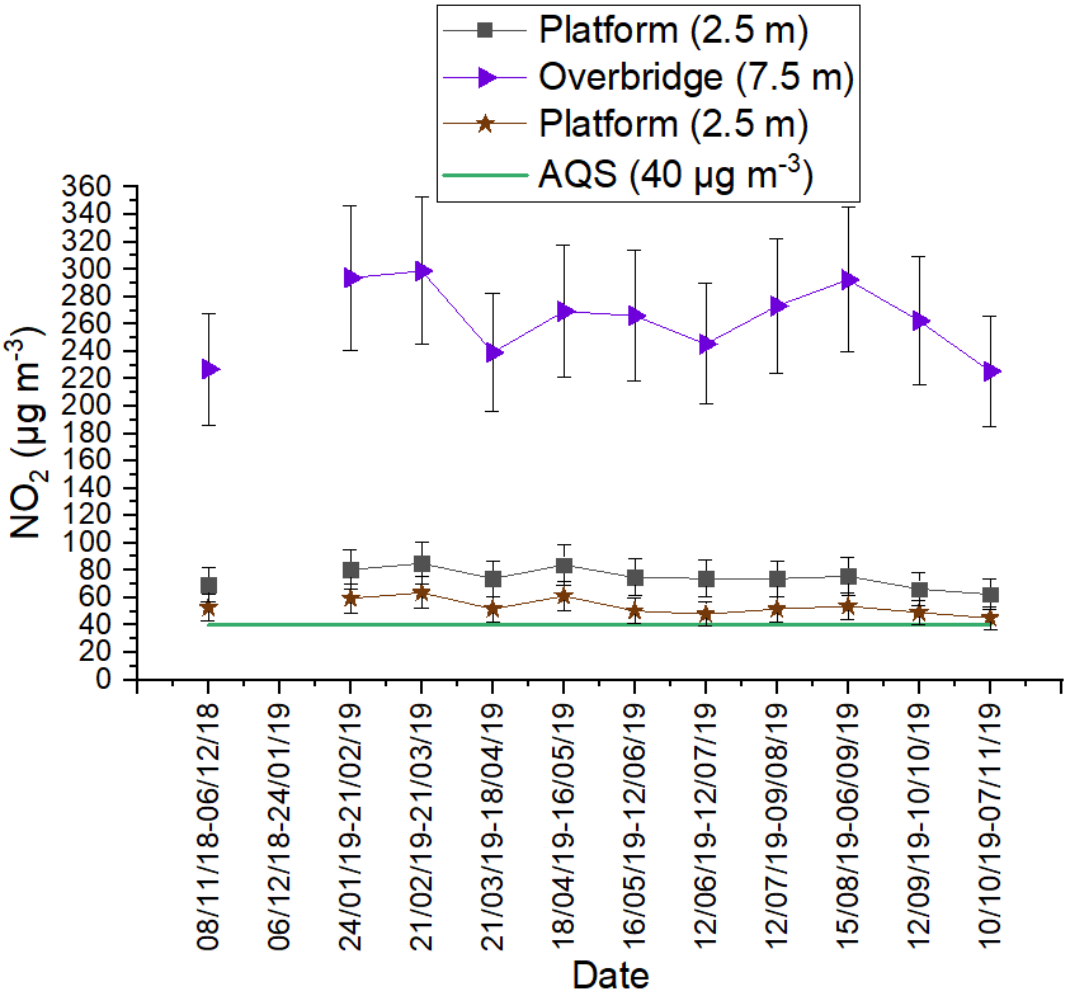


Figure 5.19 Four weekly variations in the NO_2 concentration measured by diffusion tubes between 2018 and 2019 at the Manchester Victoria station

The effect of seasonal variations with NO_2 concentrations at Manchester Victoria Station is inconsistent as seen in Table 5.13. In the coldest seasonal period of winter 2018 (data obtained from WorldMet in R for the Manchester Airport weather station) with an average ambient temperature of 6°C, the indoor NO_2 concentration was higher than that seen in much warmer seasons (Carslaw, 2022). This trend was reflected at all points in the station, at platform level of 2.7 m, on the concourse at 2.7 m and within the overbridge section, which is effectively 7.5 m above ground level. In the context of research question 4 and specifically scientific question SQ5, the data of Table 5.13 shows that seasonal variations are not a parameter that affect indoor air quality within a train station, in this case, for indoor NO_2.

Table 5.13 Seasonal variations in indoor, ground-concentration NO_2 concentrations in the Manchester Victoria train station

Season	Seasonal NO_2 concentration average (µg m^{-3})			Average ambient temperature[1] (°C)
	Platform	Overbridge	Concourse	
Winter 2018	75.0	260.4	56.2	6.0
Spring 2019	79.4	268.4	56.8	9.5
Summer 2019	74.6	270.4	51.3	16.0
Autumn 2019	64.5	244.0	47.2	9.9

[1] Manchester Airport weather station (Carslaw, 2022)

The average NO_2 concentrations at Manchester Victoria of this study were much higher than that observed in London's King's Cross which had a six-month average of 71.4 µg m^{-3} as well as Edinburgh Waverly which had an six-month average NO_2 concentration of 86.5 µg m^{-3} (Font et al., 2020). In Birmingham New Street station, Hickman et al. also conducted two-weekly average NO_2 concentrations at 306 µg m^{-3} and 358 µg m^{-3} (Hickman et al., 2018b). It is difficult to compare the Manchester Victoria station diffusion tube data directly with the Birmingham New Street station data, due to the different timescales, with 4 weekly measurements of NO_2 conducted in this study over a 1 year time frame whereas in Birmingham New Street only 2-weekly measurements of NO_2 were carried out over 2 consecutive 2 week periods, the first between 17th Oct – 01st Nov 2016 followed by 01st Nov – 15th Nov 2016. On a numerical basis, the highest four-weekly NO_2 concentration at platform level in Manchester Victoria of 154 µg m^{-3} was much lower than the highest two-weekly NO_2 concentration of 358 µg m^{-3} observed by Hickman et al. during Nov 2016 (Hickman et al., 2018b). Aside from the difference in timescale, one possible reason for the difference in NO_2 concentrations at Manchester Victoria than the other trains stations include: station geometry, train fleet stock, building dimensions and ventilation, number and density of trains, mode of train movement and operation. Birmingham New Street station, in addition is a much larger train station with 11 platforms in comparison to the 6 platforms at Manchester Victoria and so air flow patterns within the station will be different between the stations.

Table 5.14 Averaged monthly NO_2 diffusion tube data

Station Monthly NO_2 µg m^{-3}	Average µg m^{-3}	Period of monitoring	Min NO_2 µg m^{-3}	Max NO_2 µg m^{-3}
Manchester Victoria station	113	11 months	37	348
King's Cross	71.4	6 months	45.2	92.5
Edinburgh Waverly	86.5	6 months	66	114
Birmingham New Street	327	1 month	178	508

In order to determine an annual mean, for Manchester Victoria, the diffusion tube concentrations have to be processed in the LAQM Diffusion Tube Processing Tool. Within the tool, the diffusion tube data is corrected for bias using a national bias adjustment factor of 0.82, as part of determining the average. In relation to typical UK roadside, one example of a UK local government installed chemiluminescence analyser outside of Manchester Piccadilly station in the centre of Manchester. During the 2019 calendar year, at the Manchester Piccadilly roadside monitor, the annual NO_2 concentration was 36.5 µg m^{-3} with the monthly NO_2 concentrations varying between 24 – 51 µg m^{-3} (Air, 2018). In comparison, at the Manchester Victoria station the 2019 bias adjusted annual mean NO_2 concentration for at ground level was calculated to be 53.8 µg m^{-3}. Relatively close to the station, GMCA have a non-automatic monitoring site near the National Football Museum (Site ID: MA26ANO) (GMCA, 2019b; Google, 2022e). In 2019, the annual NO_2 was recorded as 33 µg m^{-3} (GMCA, 2019b). This is also lower than that observed at Manchester Victoria.

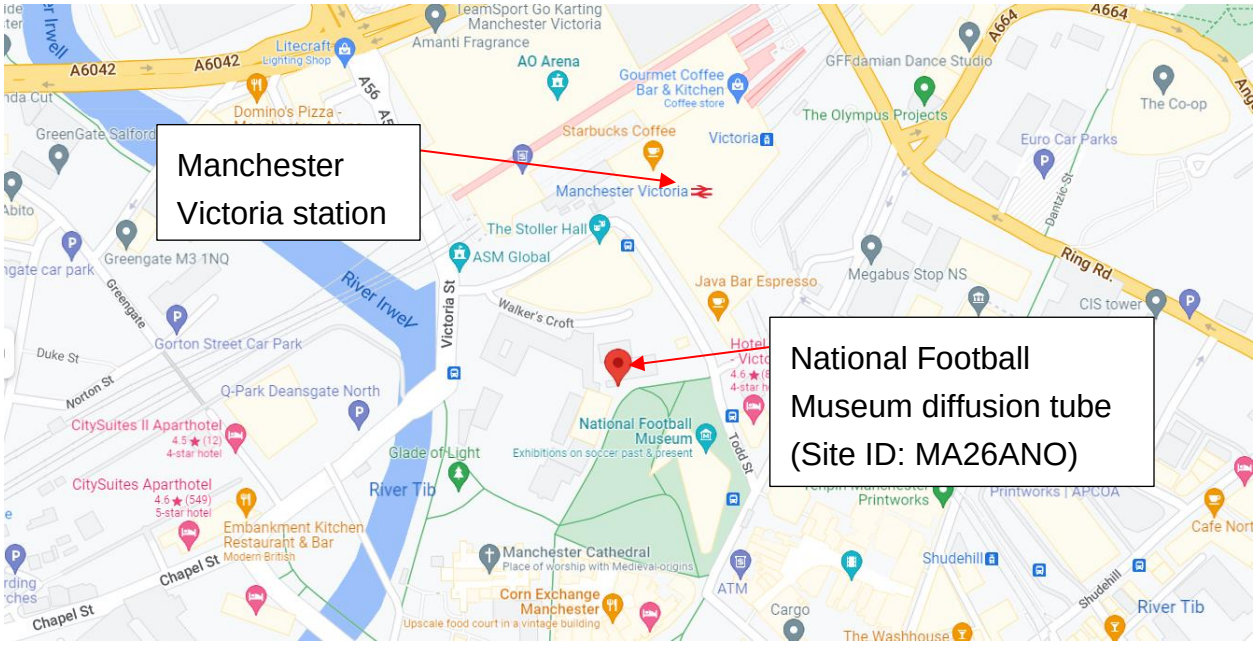


Figure 5.20 Nearest Greater Manchester non-automatic monitoring site in relation to the Manchester Victoria station (GMCA, 2019b; Google, 2022e)

For the diffusion tubes at height, positioned in the overbridge, the bias adjusted average concentration for NO_2 was 193 µg m^{-3} at 2.5 m. The annualised mean at Manchester Victoria of 53.8 µg m^{-3} is greater than that of the nearest roadside monitoring site at Manchester Piccadilly. This is greater than the UK AQS of 40 µg m^{-3} of NO_2 in 1 calendar year. It must be noted that the NO_2 UK AQS limits are not legally applicable within the repair shed , which are instead governed by WELs (workplace exposure limits) on 15 min (1910 µg m^{-3} NO_2) and 8 h (955 µg m^{-3} NO_2) time weighted average (TWA) with much higher NO_2 thresholds (DEFRA; HSE, 2005d). This indicates an inconsistency between the UK AQS limits and the UK WELs, with lenient limits inside an enclosed railway depot but more stringent limits on the roadside outside of the depot. While it is understandable that the UK AQS covers all of the public including all age groups and health conditions, in contrast to the WELs which are designed for fit-and-health workers, and so the UK AQS limits have to be more stringent than the WELs. It does however, pose a question for further research, whether the WELs should be more stringent, but this is outside of the scope of this work.

5.9 Comparison against other railway air quality studies

When considering the measurements in this study against similar air quality monitoring projects, the four-weekly averaged NO_2 concentration at all 4 of the railway depots were much lower than the NO_2 concentrations observed at Birmingham New

Street. Hickman et al. recorded two-weekly averages for NO_2 of 306 µg m^{-3} (17th Oct 2016 – 01st Nov 2016) and 358 µg m^{-3} (01st Nov 2016 – 15th Nov 2016), whereas in the railway depots, the highest NO_2 concentration was 225 µg m^{-3} (Hickman et al., 2018a). The high concentrations of NO_2 on platforms indicate, an influence of close proximity to the source and potentially limited dispersion conditions. The difference in the pollution concentrations between those observed in the railway depots of this study and a heavily polluted railway station such as Birmingham New Street station could be attributed to the differences in: train fleet stock, building dimensions and ventilation, number and density of trains, mode of train movement and operation. Birmingham New Street station caters for much larger diesel 'High-Speed trains' (HST) with Class 220/221 Voyager trains and Class 170 Turbostars whereas in the UK railway depot considered in this study, the majority of the diesel trains are small, commuter diesel trains such as the 'Pacer' Class 14X, 'Sprinter' Class 15X' and 'Express Sprinter' Class 158 units. In contrast to a railway depot, within a station, trains are constantly travelling in and out of the station where in the case of Birmingham New Street there are approximately '600 diesel train movements per day' during the working periods of 6 am – 12 am. In the railway depots however, there can be large periods of inactivity of up to 3 h in terms of engine start-up, with lighter maintenance work not requiring the engine to be started (Hickman et al., 2018a). For the Manchester Victoria station, at platform level, of 2.7 m, the four weekly NO_2 concentration varied between 43 – 65 µg m^{-3}, as seen previously in Figure 5.19. This is also much lower than that seen at Birmingham New Street.

5.10 Conclusion

In this chapter, diffusion tubes were utilised as the air quality monitoring tool for identifying variations in NO_2 concentration at fixed locations with changing season, changing height and ground concentration position. This is important as the variations in NO_2 concentration with position in the repair shed of the Neville Hill railway depot (Table 5.4) indicate that it is not well-mixed. The diffusion tube measurements have shown that there is evidence that NO_2 concentrations can increase with height within indoor railway depot environments with this observed at all 4 of the railway depots considered in this study. Building on this, a time-variant box model confirmed that the repair shed of the Neville Hill railway depot is not well-mixed, and was a poor predictor of indoor NO_2 concentration with time, when validated against typical indoor NO_2 measurement data within an 8 h period beginning at 07:30 and concluding at 15:30. It must be noted that detailed air flow measurements weren't taken as part of this work, and so there are a caveats to the indications of poor mixing demonstrated by the box

model. This is an area which could be further explored through further work, using CFD (Computational Fluid Dynamics) modelling with air flow measurements to provide detailed measurements of the mixing behaviour within Neville Hill's repair shed, supporting the indicative measurements of this study of imperfect mixing in the repair shed.

In the context of research question 4 and the accompanying scientific questions, this chapter has demonstrated that seasonal variations, (indoor) temperature and height are factors which affect indoor air in a railway depot. The temperature gradient behaviour observed within an indoor environment, show similar trends in increasing concentrations of a pollutant with height, as literature (MacCarty et al., 2020; Johnson et al., 2011). The increases in indoor temperature with height of Figure 5.2 are also in alignment with similar studies such as that of Boon and Battams (Boon and Battams, 1988), who observed increasing vertical temperature with increasing height within environments with poor air mixing within an indoor livestock facility. This has demonstrated a novel area where this study has expanded on current literature in a new environmental setting.

This study has also put into context the indoor NO_2 concentrations measured within the railway depots of this study against the UK AQS of 40 µg m^{-3}, with three of the four railway depots having bias corrected annualised NO_2 ground level concentrations above this UK AQS limit. These were at the Heaton, Newton Heath and Neville Hill railway depots. In addition, all four of the railway depots had annualised NO_2 concentrations above the WHO air quality guideline value of 10 µg m^{-3} NO_2 annually (WHO, 2021a). It must be noted that this annual NO_2 UK AQS limit and WHO air quality guidelines values are not legally applicable to UK railway depots, which are classed as indoor spaces, however the UK AQS and WHO guidance values do provide a benchmark against what is deemed to be acceptable levels of clean air for the general public, and are useful comparative measures.

Expanding on the railway depot measurements, additional work has conducted the diffusion tube measurements conducted at the Manchester Victoria train station in Manchester with an annualised mean of 53.8 µg m^{-3}. The data has shown that the within the overbridge section of the station, there are some early indications of a concentration gradient with much higher NO_2 concentrations observed within the overbridge than platform level. The diffusion tube data at Manchester Victoria station has shown that station geometry is parameter that affects air quality in a UK train station answering research question 4: 'What type of parameters affect the air quality of UK railway depots and train stations where diesel trains are in operation?' However, seasonal variations were shown to have very little effect on indoor NO_2

concentrations within the station, in contrast to the trend seen within the 4 railway depots.

Chapter 6 Transient air quality monitoring in a UK railway depot

6.1 Overview

This chapter will assess the transient air quality measurements of 4 Northern Rail's railway depots in the UK in order to partly address research question 4:

R4: What type of parameters affect the air quality of UK railway depots and train stations where diesel trains are in operation?

A number of scientific questions have been formulated to support research question 4 and are as follows:

SQ11: How does the NO_2 and $PM_{2.5}$ indoor concentration vary with time within the repair shed of the Neville Hill railway depot?

SQ12: Is there a particular train type which contributes significantly to indoor air pollution within the repair shed of the Neville Hill railway depot?

SQ13: How do the transient NO_2 concentrations within the repair shed of Neville Hill compare against the UK's hourly NO_2 ambient air quality standard and with other studies of semi-enclosed environments dominated by rail emissions?

Transient air quality monitoring is an assessment method for determining the instantaneous air quality on minute and hourly time scales in contrast to static monitoring where tools such as diffusion tubes are used for 2-4 wk monitoring periods. For this study, as outlined previously in the methodology chapter, transient monitoring of NO (nitrogen oxide), NO_2, NO_x and $PM_{2.5}$ were conducted in the middle of the repair shed of the Neville Hill railway depot. For the species NO, NO_2, and NO_x, a Horiba APNA 370 chemiluminescence analyser was utilised for monitoring the indoor, ground level concentrations (ppb) on a 3 min timescale at a height of 0.9 m. For monitoring $PM_{2.5}$ concentration, an AirVisual Pro was utilised with a timescale of 10 s, at a height of 0.5 m. The indoor, ground level temperature (T_e) at 0.5 m was also recorded by the AirVisual Pro on a 10 s timescale. Due to its' low-cost technology, a correction factor of 0.86 was applied to the $PM_{2.5}$ concentration data gathered from the AirVisual Pro, based on a co-location study conducted by Zamora et al., as discussed previously in the methodology chapter (Chapter 3) (Zamora et al., 2020). Transient monitoring of NO_x was conducted between the 3rd Dec – 11th Dec, 2020 using a Horiba APNA 370 chemiluminescence analyser. Train movement

logs were recorded between the 7th –11th Dec, 2020 during the hours of 7:30 am and 3.30 pm, which noted in particular the numbers of carriages from each of the train types. These included the N150 (representing 150 carriages), N155 (representing 155 carriages), N158 (representing 158 carriages) and N170 (representing 170 carriages). The NO_x and $PM_{2.5}$ data was quality assured by removing data above predefined upper and lower boundaries for NO_x and $PM_{2.5}$ and by screening out values outside of the mean ± 3 σ using the approach of Balogun et al. (Balogun et al., 2010). For NO_x, this upper threshold was set at 0.25 ppm (478 μg m^{-3}) on a 3 min timescale, and for $PM_{2.5}$ at 200 μg m^{-3} on a 10 s timescale, with concentrations greater than these maximum concentrations classified as outliers.

6.2 Daily variations of air pollution levels at the middle of the repair shed of the Neville Hill railway depot

During the monitoring campaign, increases in indoor, ground-level NO_2 concentration ($[NO_2]$) were observed within the repair shed coinciding with periods of train testing activity during the 7 days sampled. Due to the varying train testing schedule, train tests could take place at any time during a 24 h period. The maximum indoor, ground level NO_2 concentration ($[NO_{2,\,max}]$) on a 3 min timescale was measured at 765 μg m^{-3} and the minimum NO_2 concentration ($[NO_{2,\,min}]$) was 29 μg m^{-3}. The data capture was 86% after quality assurance protocols. In an indoor depot environment, the workplace exposure limits (WELs) are the legally enforceable measure for assessing the air quality. For NO_2, there are 2 WELs, the 15 min STEL (short term exposure limit) of 1 ppm and the 8 h TWA (time weighted average) of 0.5 ppm (HSE, 2005b). During the 7 days of the campaign period, the 8 h TWA NO_2 concentrations ($[NO_{2,\,8\,h\,TWA}]$) were much lower than the 8 h TWA standard of 0.5 ppm, with $[NO_{2,\,8\,h\,TWA}]$ concentrations ranging from 0.05 to 0.10 ppm as seen in Figure 6.1. The 8h TWA period was set for a typical working period of 7.30 am to 3.30 pm. Details on how the STEL (short term exposure limit) and TWA (time weighted average) values are calculated are detailed in the earlier methodology chapter (Chapter 3).

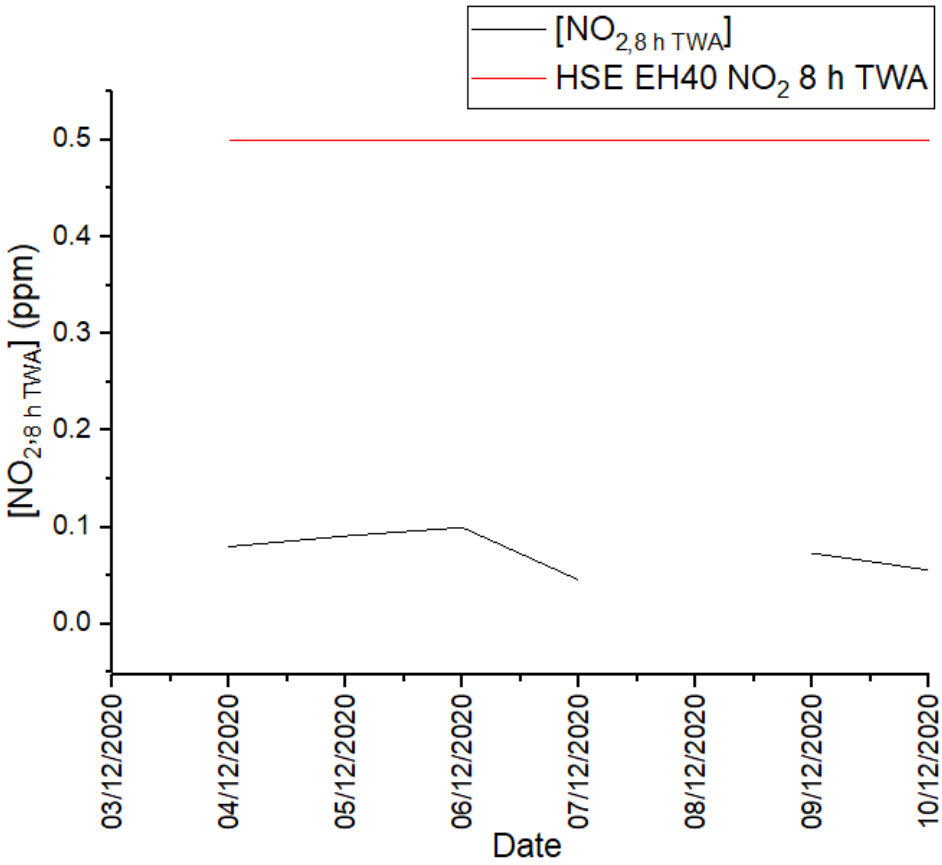


Figure 6.1 Comparison of indoor, ground-level NO_2 concentration in the repair shed of the Neville Hill railway depot benchmarked against the EH40 WEL over an 8 h time averaged period.

The NO_2 concentration data of the repair shed can also be compared against the UK AQS of 200 µg m^{-3} (hourly average) as set by DEFRA which although it has no legal effect in an indoor enclosed environment, is an interesting point of comparison. The UK ambient air quality standard is a benchmark used to determine acceptable levels for general public in outdoor environments within the UK (DEFRA). As seen in Figure 6.2, the hourly data showed peaks during at different periods of time across the available data from the 3rd Dec until the 11th Dec. There was no consistent trend in the peaks, which can be attributed to unpredictable train maintenance schedules at the depots, where trains require the engine to be started at any particular time. Interestingly, the indoor, ground level hourly-averaged NO_2 concentrations ([$NO_{2,\ h\text{-}av,}$]) were noted to be above 200 µg m^{-3}, on 25 instances, out of a total of 192 data points of [$NO_{2,\ h\text{-}av,}$] during the period of monitoring covering approximately 9 days. This is a significant number of hourly NO_2 exceedances observed in such a short time frame, with the potential for up to 1015 exceedances of hourly NO_2 in a calendar year, based on a reasonable assumption that the train maintenance schedule is assumed to be the same throughout the year. It must be

noted that there is a caveat to the UK's AQS for hourly NO_2 concentration of 200 µg m^{-3} over a 1 year period within outdoor environments, with 18 allowable exceedances above the hourly NO_2 concentration limit of 200 µg m^{-3} , permitted within a calendar year (DEFRA). Although the exceedances in this study were noted in an indoor environment, it is interesting to note that if these conditions had occurred in an outdoor setting, then the allowable number of hourly NO_2 exceedances would have been surpassed after only 7 days. When looking at WHO guidelines, for indoor and outdoor environments, the guidance for NO_2 is much stricter with an hourly guidance value of 200 µg m^{-3} with no permitted exceedances and a daily NO_2 guidance value of 25 µg m^{-3} (WHO, 2021a). The WHO guidelines have no legal effect in the UK, however, if these were adopted into law, the repair shed considered in this study would have NO_2 concentrations in exceedance of the guidance limits for both the hourly NO_2 guidance values, as noted earlier with 9 exceedances, as well as the daily NO_2 guidance value, as seen in Table 6.1 with exceedances on every single day.

Table 6.1 Daily NO_2 concentration of indoor, ground-level NO_2 concentration in the repair shed of the Neville Hill

Date	Daily NO_2 (µg m^{-3})	Data capture (%)	In exceedance of WHO daily guideline of 25 µg m^{-3} NO_2
04/12/2020	173	38	Yes
05/12/2020	200	100	Yes
06/12/2020	146	92	Yes
07/12/2020	126	100	Yes
08/12/2020	135	100	Yes
09/12/2020	139	100	Yes
10/12/2020	135	92	Yes
11/12/2020	76	63	Yes

The concentrations of [$NO_{2,\ h\text{-}av,}$] gathered in this study, highlight the weaknesses in the current WELs for NO_2, with much higher thresholds on both a 15 min timescale (1910 µg m^{-3}) and an 8 h TWA timescale (955 µg m^{-3}) (HSE, 2005b). Hickman et al., also noted a discrepancy between the NO_2 limits set as safe for workers in an indoor environment within the WELs and the limits set for the general public in outdoor settings (Hickman et al., 2018b). One reason provided for this difference in NO_2 limits is that the UK ambient air quality standard of 200 µg m^{-3} is designed to protect all public including vulnerable groups such as the elderly, pregnant women and young children, and that the WELs are not designed typically for these vulnerable groups (DfT, 2021d). Unfortunately, this has created a two tier

system where workers in indoor environment are expected to tolerate breathing in higher quantities of pollutants such as NO_2.

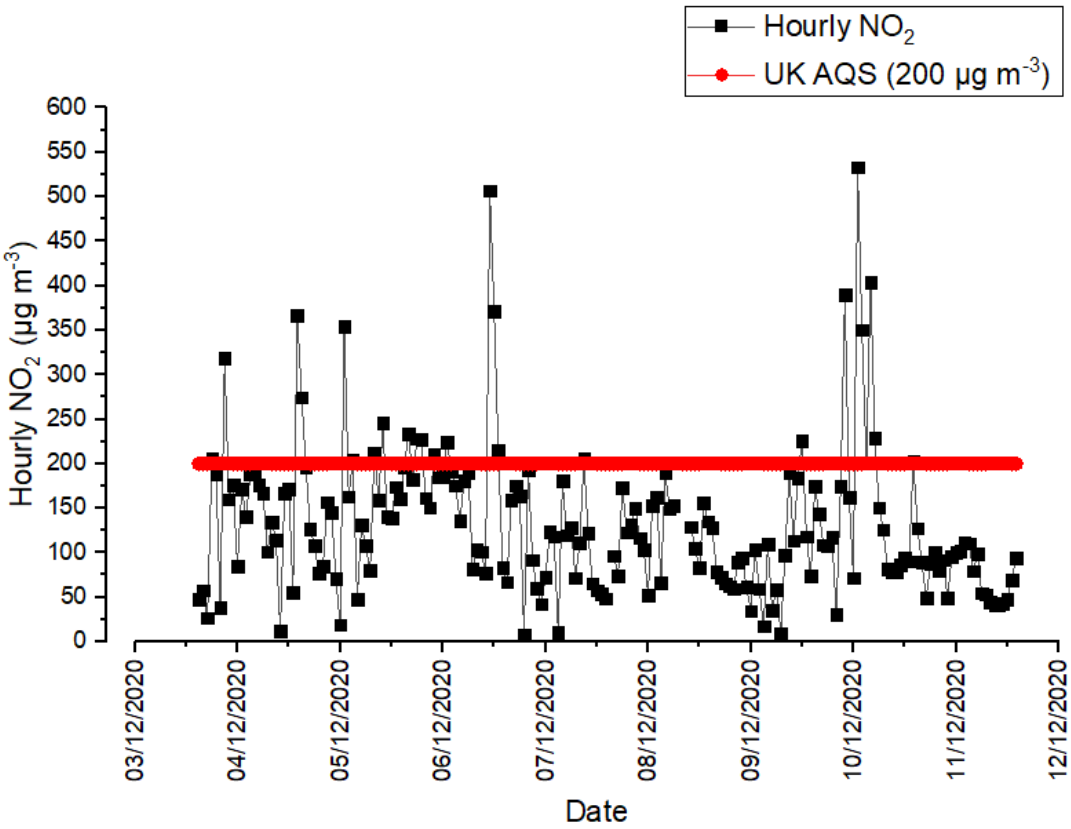


Figure 6.2 Indoor, ground level hourly averaged NO_2 in the repair shed of the Neville Hill railway depot compared against the UK hourly NO_2 AQS

For the $PM_{2.5}$ concentrations measured in the repair shed, the highest $PM_{2.5}$ concentrations ($[PM_{2.5,\,max,}]$) on a 10 s timescale after removing any outliers, was 43 µg m^{-3}. The indoor, ground level hourly-averaged $PM_{2.5}$ concentration ($[PM_{2.5,\,h\text{-}av,}]$) in the repair shed varied between 1.3 – 21.0 µg m^{-3} as seen in Figure 6.3. The data capture was 80% after quality assurance protocols. In terms of hourly $PM_{2.5}$ concentrations, Font et al. reported $PM_{2.5}$ concentrations of between 9.9 –11.9 µg m^{-3} at Edinburgh Waverley station and 7.2 –14.5 µg m^{-3} at London King's Cross station (Font et al., 2020).

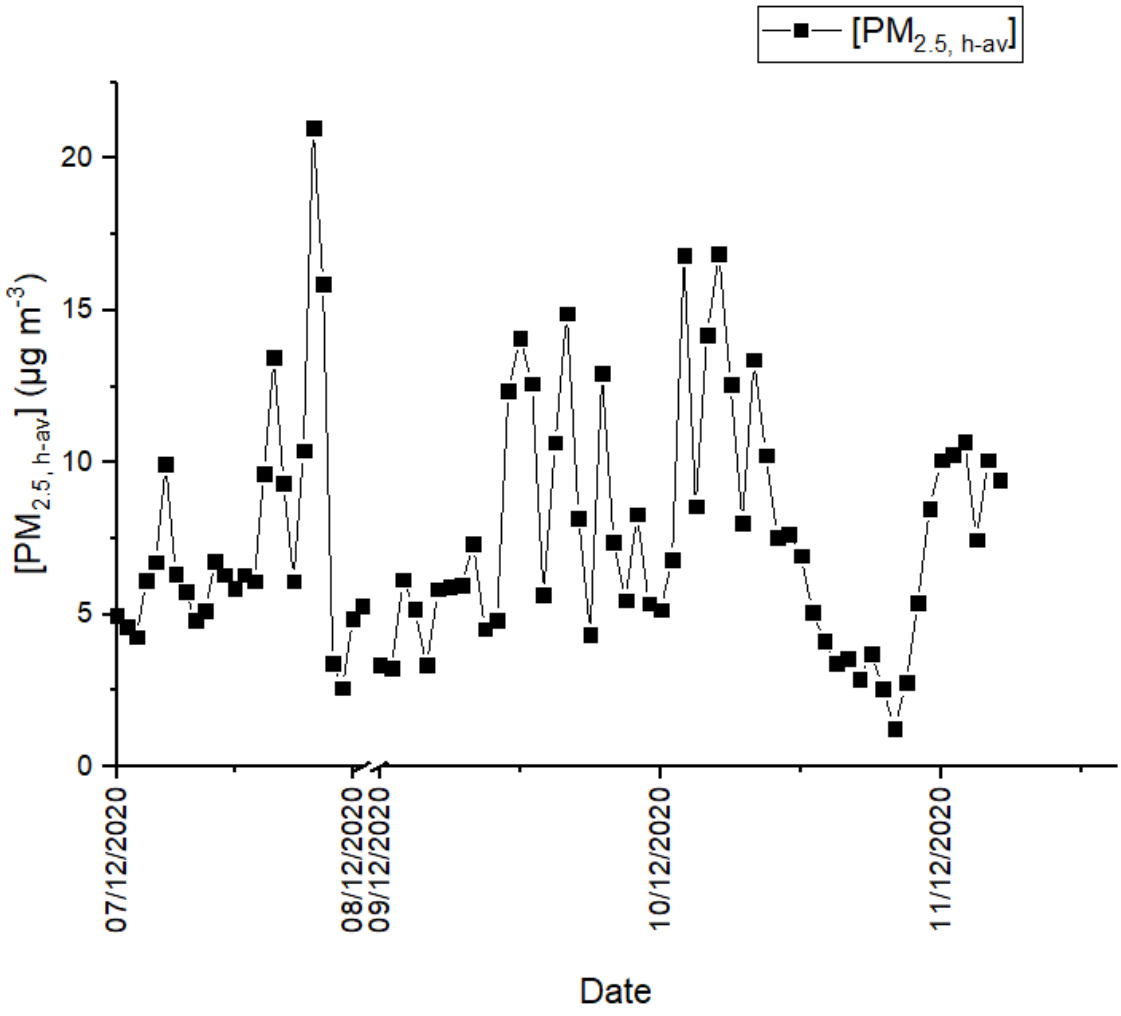


Figure 6.3 Indoor, ground level, hourly-averaged $PM_{2.5}$ in the repair shed of the Neville Hill railway depot

There are many reasons why the hourly-averaged $PM_{2.5}$ concentrations, of Figure 6.3 may be much lower than similar timescale $PM_{2.5}$ concentrations in a typical train station, attributable to a number of factors including: train fleet stock, building dimensions and ventilation, number and density of trains, mode of train movement and operation. At a station, trains are constantly travelling in and out of the station during the working periods of 6 am – 12 am, whereas in the repair shed there can be large periods of inactivity of up to 3 h in terms of engine start-up, with lighter maintenance work not requiring the engine to be started. This can explain the lower end of the hourly $PM_{2.5}$ concentration range of 1.3 µg m^{-3}, observed in the repair shed of this study.

Unfortunately, for $PM_{2.5}$ there is no dedicated WEL standard and often black carbon WELs and respirable dust COSHH standards are used as de-facto benchmarks for $PM_{2.5}$ for an indoor environment. Black carbon, a constituent of

$PM_{2.5,}$ has an 8 h TWA WEL of 3500 µg m^{-3} and respirable dust has an advisory COSHH WEL limit of 4000 µg m^{-3}. In the UK, there is currently no short term $PM_{2.5}$ UK AQS, for 1 h and 24 h periods. Instead, there is an annual UK AAQS for $PM_{2.5}$ of 20 µg m^{-3}, however there is insufficient data from this study to compare against this annual UK AQS for $PM_{2.5}$ (DEFRA). There is however, a daily $PM_{2.5}$ standard guideline of 15 µg m^{-3} set by the WHO (World Health Organisation), which although has no legal effect in the UK, is a useful barometer for $PM_{2.5}$ concentration in the repair shed of 9.2 µg m^{-3} (WHO, 2021a) Cities within the UK, have devolved powers to set their own air quality limits, with Leeds planning to adopt the WHO $PM_{2.5}$ standard, by 2030 in the Leeds City Centre, in outdoor environments, however, this jurisdiction does not extend to indoor environments or outdoor rail facilities such as train stations which are under the remit of the HSE (Health and Safety Executive) (LCC, 2021).

From the available data of this study, the daily $PM_{2.5}$ concentration was not in exceedance of the 24 h WHO $PM_{2.5}$ standard of 25 µg m^{-3} on the only day of 24 h data for the repair shed, with a daily $PM_{2.5}$ concentration of 10 µg m^{-3} measured on the 10th Dec, 2020 (WHO, 2005). When compared against similar studies in rail environments, the daily $PM_{2.5}$ concentration within the Neville Hill railway depot of this study is much lower than observed in the daily $PM_{2.5}$ in train stations such as Birmingham New Street and London Paddington. In the Birmingham New Street train station, Hickman et al., reported daily $PM_{2.5}$ concentrations of between 10 –80 µg m^{-3}, with the lower end of the concentration observed in the post-Christmas period of 2016 and the higher end observed in early January of 2017 (Hickman et al., 2018b). In London Paddington, Chong et al. reported daily $PM_{2.5}$ concentrations of between 4 – 40 µg m^{-3}, during a five day period in September 2012 (Uven et al., 2015). As noted previously, the difference in operational practices between a railway depot and a train station, is one of the potential reasons for the much lower daily $PM_{2.5}$ concentration of this study, with large periods of inactivity with the engine switched off, observed in a depot environment. Stations also are much larger than railway depots and so have a greater number of platforms, to accommodate trains than within a railway depot. Consequently, within a station, there are potentially a larger quantity of trains idling at platforms than would be seen in a depot. However, idling times at stations typically limited to 10 min whereas in a depot, idle times can run for up to 2 h depending on the maintenance work required (Wang, 2014). The rail industry collectively has acknowledged the problems with excessive idling at both train stations and railway depots, negatively affecting air quality and through the rail delivery group (RDG), a governing body for the rail industry, guidance has been

issued as of July 2021 to reduce idling times through better operational practices (ORR, 2014). In a depot, the RDG recommends the use of shore supplies, electrical power supply units, to switch on a train for maintenance instead of starting up the engine and combusting diesel fuel unnecessarily. In a station, it is recommended by the RDG to shut down trains on arrival into platforms unless the train is scheduled to start a new journey or continue its journey within a short period of time (RDG, 2021).

In terms of legislative standards, as mentioned in the earlier paragraph, an absence of dedicated UK $PM_{2.5}$ WELs makes things challenging for assessing compliance for $PM_{2.5}$ in a depot environment or by extension within train stations. The daily WHO guideline of 25 μg m^{-3} whilst a useful benchmark for comparing $PM_{2.5}$ data against, as a health based standard; it has no legal effect within the UK. The UK Government has however, acknowledged this gap within the UK WELs set by the HSE for $PM_{2.5}$ and PM_{10}, and has initiated research through the Department for Transport (DfT) to develop new, additional targets for $PM_{2.5}$, PM_{10} and NO_2, within train stations for deployment in 2022 as an advisory measure, with a plan to meet these targets in 2030 (DfT, 2021d). This will be supported by the deployment of a UK rail air quality monitoring network (AQMN), by the RSSB on behalf of the DfT, covering 100 train stations across the UK, beginning in summer 2021, as well as further research into improving air quality within stations as well as on-board trains (RSSB, 2021c; DfT, 2021c).

6.3 Statistical analysis

6.3.1 Multivariate linear regression

6.3.1.1 **NO_x**

Multivariate linear regression analysis was performed to evaluate whether a statistically significant relationship existed between the numbers of carriages present for four different train types (see Appendix F for code in R). 4 explanatory variables were used for the regression to denote the number of carriages for each train type, N150 (number of 150 carriages), N155 (number of 155 carriages), N158 (number of 158 carriages) and N170 (number of 170 carriages). An additional explanatory variable, was also included in the regression to represent the indoor, 3 min-averaged temperature at ground level ($T_{e,\ 3min\text{-}av}$) within the centre of the repair shed of the Neville Hill railway depot. The independent variable was set as the indoor ground level, 3 min-averaged NO_x ([$NO_{x,\ 3min\text{-}av}$]) within the same location within the Neville Hill railway depot and was measured in units of ppm. A greater time resolution was

used for the regression at 3 min in contrast to the earlier hourly concentrations, in order to get a better cross-reference against train movement times which were on a 1 min timescale. Using an hourly time resolution, tended to average out the number of train movements, for hourly NO_x concentrations, with a much smaller sample size, and made it difficult to identify trends between the explanatory variables and the independent variable of NO_x concentration, in particular for statistical significance.

Hence, a time resolution of 3 min was used instead for the multivariate linear regression, based on the shortest timescale of 3 min available from the raw data. The statistical analysis determined an R^2 of 0.21 for the relationship between the four explanatory variables and the independent variable of [$NO_{x,\ 3min\text{-}av}$]. This means that only 21 % of variance is explained by the variability within these factors, with the remaining 79% variance unexplained. The low R^2 value of below 0.25 indicates a weak correlation between the explanatory variables and [$NO_{x,\ 3min\text{-}av}$]. The weak correlation and unexplained variance can be attributed to the discrete values of the number of carriages for each train type, which create a non-linear trend. From the explanatory variables, it was expected that the 170 train type would have statistical significance with respect to [$NO_{x,\ 3min\text{-}av}$], since in Chapter 4, this train type was found to have particularly high engine exhaust emissions for NO_x in terms of engine exhaust concentrations, with 250 ppm at idle (notch 0) and 1500 ppm (at full power). In addition, this 170 train had no engine after-treatment system and consequently there was no post-combustion to convert the engine exhaust NO_x into N_2 (nitrogen) and H_2O (water vapour). The multivariate regression analysis confirmed this trend, with an extremely high statistical significance between the N170 and [$NO_{x,\ 3min\text{-}av}$], with a p-value very much smaller than 0.05. This statistical significance was also seen with N155 with an extremely high significance between N155 and [$NO_{x,\ 3min\text{-}av}$] as seen in Table 6.2 through the very small p-value. A p-value below 0.05 indicates that there is statistical significance for the explanatory variable, and indicates that there is less than a 5% probability that the relationship between the explanatory variable and independent variable is due to random chance. In additional to statistical significance between some of train types and [$NO_{x,\ 3min\text{-}av}$], the variable $T_{e,\ 3min\text{-}av}$ also had an extremely high statistical significance with [$NO_{x,\ 3min\text{-}av}$], demonstrating the strong link between indoor temperature and indoor NO_x. This answers research question 4, with both train type and indoor temperature both having an effect on indoor air quality.

Table 6.2 Linear regression of [$NO_{x,\ 3min\text{-}av}$] with train type and $T_{e,\ 3min\text{-}av}$ in the repair shed of the Neville Hill railway depot

Variable	Regression coefficient	Std. Error	t value	p value P*r(>t)*
y-intercept	-215.620	34.279	-6.29	6.26E-10
N150	-27.698	20.998	-1.319	0.188
N155	69.346	8.951	7.747	4.24E-14 ***
N158	-5.720	-3.102	-1.844	0.066
N170	19.147	3.538	5.412	9.13E-08 ***
$T_{e,\ 3min\text{-}av}$	20.002	2.107	9.494	<2E-16 ***

p-value: * <0.05 significant **0.01 very significant ***0.001 extremely significant

6.3.1.2 $PM_{2.5}$

A similar statistical analysis was carried out for the indoor, ground level, hourly-averaged $PM_{2.5}$ concentration data, and the five explanatory variables of N150, N155, N158, N170 and $T_{e,\ 1min\text{-}av}$ (indoor ground level 1 min-averaged temperature). With an R^2 of 0.08 for the relationship between the four explanatory variables and the independent variable of indoor, ground level, 1 min-averaged $PM_{2.5}$ concentration ([$PM_{2.5,\ 1min\text{-}av,}$]) this means that only 8% of variance is explained by the total variance, the remaining 92% of the variance is unexplained. A greater time resolution was used for the regression at 1 min, in order to get a better cross-reference against train movement times which were on a 1 min timescale. Similar to the NO_x regression, using an hourly time resolution for $PM_{2.5}$ concentration, tended to average out the number of train movements, for hourly $PM_{2.5}$ concentrations, with a much smaller sample size, and made it difficult to identify trends between the explanatory variables and the independent variable of $PM_{2.5}$ concentration, in particular for statistical significance. Hence, a time resolution of 1 min was used instead for the multivariate linear regression, based on direct alignment with the train movements recorded every minute. From Table 6.3, three of the four explanatory variable were seen to have statistical significance. These were N155, N158 and $T_{e,\ 1min\text{-}av}$. In particular for N155 and N158, the statistical significance was extremely significant with respect to [$PM_{2.5,\ 1min\text{-}av,}$] with both variables having a p-value less than 0.001. This difference in statistical significance between N170 and the N155 & N158 could be due to the engine type. The N155 and N158 both use a Cummins NTA 855 engine with a higher emission factor for PM_{10} (0.46 – 0.82 g kWh^{-1}) than that of N170 which has a MTU 6R183TD13H engine with a lower emission factor range for PM_{10} (0.1 – 0.2 g kWh^{-1}), as noted previously in Chapter 4 (I., 2006b; Gibbs et al., 2020). Due to a lack of available data for $PM_{2.5}$ emission factors, it is assumed that a similar relationship is observed for $PM_{2.5}$ as seen in the PM_{10} emission factors of Chapter 4, with higher $PM_{2.5}$ emission factors for N155 and N158,

as compared against N170 (I., 2006b). The Cummins NTA 855 engine is a much older engine with a manufacturing date tracing back to 1985, whereas the MTU 6R183TD13H engine was manufactured much later in 1999-2005, and so the improvement in PM_{10} through its' lower emission factor can be attributed to better engine combustion technology. It is difficult to pinpoint what specific improvements have been made in engine design from the N155 and N158, to N170, due to limited data. It must be noted that none of the trains in this study have engine after-treatment technology. In terms of $T_{e,\ 1min\text{-}av}$, multivariate regression showed a very significant, statistical relationship between $T_{e,\ 1min\text{-}av}$ and [$PM_{2.5,\ 1min\text{-}av,}$]. With indoor temperature having statistical significance with both [$NO_{x,\ 3min\text{-}av}$] and [$PM_{2.5,\ 1min\text{-}av,}$], it can be concluded that both of these variables are significant parameters contributing to indoor air quality in a railway depot, answering research question 4.

Table 6.3 Linear regression of [$PM_{2.5,\ 1min\text{-}av,}$] with train type and $T_{e,\ 1min\text{-}av}$ in the repair shed of the Neville Hill railway depot

Variable	Regression coefficient	Std. Error	t value	p value P*r(>t)*
y-intercept	-5.494	2.180	-2.729	0.006 **
N150	-1.545	1.356	-1.139	0.255
N155	5.117	0.634	8.075	1.18E-15 ***
N158	2.557	0.265	9.648	<2E-16 ***
N170	-0.333	0.214	-1.558	0.119
$T_{e,\ 1min\text{-}av}$	0.852	0.134	6.353	2.63E-10 ***

p-value: * <0.05 significant **0.01 very significant ***0.001 extremely significant

6.4 Conclusion

This chapter has shown that at the Neville Hill railway depot within its' repair shed, the hourly indoor concentrations of NO_2 are greater than the UK AQS of 200 µg m^{-3}, with 192 observances greater than 200 (Figure 6.2). Whilst there is no legal requirement for the concentrations of NO_2 to comply to the UK AQS since this is a standard for outdoor environments, it is a useful comparison to gauge how good or bad the air quality is within rail environments such as railway depots. Similarly observations for $PM_{2.5}$ within the same repair shed, with hourly concentrations of $PM_{2.5}$ greater than the 20 µg m^{-3} (Figure 6.3). With an absence of a dedicated hourly standard for $PM_{2.5}$, the annual UK AQS annual limit of 20 µg m^{-3} was used as a reference point, for benchmarking the $PM_{2.5}$ concentrations in the depot against. Limitations in this study, prevented monitoring extending beyond 10 days, and this is an area of further work, to see what the annual $PM_{2.5}$ concentration would be within

the repair shed. Indicatively, based on the typical daily maintenance schedule within the depot, with periods of inactivity of 3 h or greater during of a typical daily schedule where the hourly $PM_{2.5}$ concentration drops to below 5 µg m^{-3}, the annual $PM_{2.5}$ concentration is likely to lie below the UK AQS 20 µg m^{-3}.

This study as well has built on the work of Font et. al to allocate air pollution to a specific train, but in new context, with this study focussed within a railway depot in contrast to Font et al.'s study within train stations (Font et al., 2020). Different methods were used however, with multivariate regression in this study in contrast to the random forests utilised in the Font et al. study (Font et al., 2020).

In the case of the Neville Hill railway depot's repair shed building, multivariate linear regression showed that the 170 train is the highest contributor (Table 6.2) to indoor, ground level 3 min NO_x concentrations within the repair shed of the Neville Hill railway depot aligning with findings in the earlier Chapter 4 which noted the 170 train as having a high emission factor for NO_x on idle power. For $PM_{2.5}$, the 155 and 158 train were determined to be extremely statistically significant (Table 5.3) with respect to the indoor, 1 min-averaged $PM_{2.5}$ concentration at ground level, which could be explained through the high emission factor of PM on idle power, for both these trains. The indoor, ground level temperature was also found to be statistically extremely significant as a parameter affecting both indoor $PM_{2.5}$ and NO_x concentration. This builds on the findings on Chapter 5, in which temperature was found to be a parameter which affected indoor air quality, where in Chapter 5, a positive temperature gradient was noted with changing height.

The data in this chapter has demonstrated that indoor, ground level temperature and train type are statistically significant parameters which affect the indoor air quality within a UK railway depot, answering research question 4 of 'What type of parameters affect the air quality of UK railway depots and train stations where diesel trains are in operation?' There are areas in which this study could be further expanded through further work where different regression techniques could be tested to determine the attribution of pollution to a particular train, and accounting of collinearity of temperature and height. The random forests method, utilised by Font et al. is one such method, that could be tested as part of this (Font et al., 2020).

Chapter 7 Conclusion and future work

7.1 Summary of contributions

In this study, four research questions have been evaluated for the work:

R1: What are the emission levels of Northern Rail DMUs in a railway depot, and how do these emissions compare to other vehicles?

R2: What are the WTW life cycle impacts which need to be considered when introducing alternative fuels into diesel-powered trains?

R3: What factors need to be considered when introducing alternative fuels into diesel-powered trains?

R4: What type of parameters affect the air quality of UK railway depots and train stations where diesel trains are in operation?

In addition, several scientific questions were formulated to support research question 4.

For research question 1, which requested a comparison of the emission concentration of Northern DMUs in a railway depot vs. emissions of other vehicles. This was majorly addressed in section 2.5.2 within the literature review, which discussed rail emission testing of a similar fleet of vehicles to Northern Rail's DMUs and referenced against all legislative emission standards. These tests conducted by the RSSB included applied load tests on the engine under test and is more representative measure of the actual emission observed during typical use. For this project, additional emission measurements were conducted on a selection of train traction types similar to those in the RSSB, however, limitations to the testing conditions, meant that the engine tests were conducted without applied load, and would therefore under predict the emission concentration as compared to the RSSB test. Respectively, the diesel emission flow rates obtained from the DMUs in this study are: CO (150: 0.0003-0.00046 g s^{-1}, 153: 0 g s^{-1} 158: 0.001-0.011 g s^{-1}), NO (150: 0.011-0.593 g s^{-1}, 153: 0.015-0.633 g s^{-1}, 158: 0.020-0.473 g s^{-1}), NO_2 (150: 0.001-0.022 g s^{-1}, 153: 0.003-0.020 g s^{-1}, 158: 0.002-0.027 g s^{-1}), NOx (150: 0.007-0.615 g s^{-1}, 153: 0.016-0.649 g s^{-1}, 158: 0.021-0.499 g s^{-1}), THC (150: 0.009-0.103 g s^{-1} , 153: 0.009-0.029 g s^{-1}, 158: 0.021-0.499 g s^{-1}) and CO_2 (150: 1.28-22.83 g s^{-1}, 153: 1.10-23.39 g s-1, 158: 2.06-25.89 g s^{-1}).

For research question 2, the WTW life cycle impacts of replacing diesel fuel in 15X DMU train were investigated. UCO HVO showed the most promising life cycle

benefits with improvements in NO_x and GHG across the fuel supply chain. In addition, reductions in combustion emissions, for UCO HVO, with an estimated 5% reduction in exhaust NO_x and 42% reduction in exhaust PM_{10}, make it a potential option to improve indoor air quality within railway depots via reduced diesel exhaust emissions. GTL also showed improvements in NO_x (6%) and GHG (49%) across the fuel supply chain. It however, had significant increases in WTW PM_{10} emissions (556%) compared to low sulphur diesel. GTL similar to HVO also showed improvements in combustion emissions with a 6% reduction in NO_x and a 28% reduction in PM_{10}, also make an option to improve indoor air quality within depots. Canola HVO showed a reduction in WTW NO^x (3%), however, it had increases in both PM_{10} WTW (%) and GHG WTW (%). Similar to UCO HVO, it showed improvements in combustion emissions with a 5% reduction in exhaust NO_x and a 42% reduction in exhaust PM_{10}.

For research question 3, the factors affecting the introduction of alternative fuels into Northern's DMU fleet were evaluated. These factors included cost, availability, sustainability and policy support acted as disincentives to the introduction of these fuels to replace alternative fuels, with often a higher price per litre vs. in-use red diesel for both fuels, with a 90% increase in fuel costs with HVO and a 25% increase in annual fuel costs with GTL.

For research question 4, the indoor air quality was evaluated within 4 railway depots and 1 train station. 11 scientific questions were formulated to support this particular research question.

SQ1. Are there seasonal variations in the indoor air quality within the railway depots of the study?

Seasonal variations were another factor affecting the concentration of indoor, air quality, as higher concentrations of NO_2 were observed during the winter months of 2018 as compared to the summer months of 2018. Within the railway depots, the colder weather in the winter month periods resulted in the reduction of natural ventilation as the shed doors were kept closed to retain heat within the depot building for worker conform. Whereas in the summer months, which much warmer average temperature the shed doors are kept open, allowing for natural ventilation to combine with the mechanical ventilation (from the 20 ceiling roof extraction fans) in a mixed-mode ventilation system.

SQ2. Is there evidence of temperature gradient behaviour within any of the four railway depots of this study?

There is evidence of temperature gradient within one of the railway depots of this study, at the Neville Hill depot within the repair shed building.

SQ3. Is there evidence of pollutant concentration gradient within any of the four railway depots of this study?

There is evidence of a concentration gradient within all four of the railway depots of this study, with increases in monthly NO_2 concentration with height. In particular, at the Neville Hill depot's repair shed, the monitoring of NO_2 over static periods within the shed showed that indoor temperature had a substantial effect on the concentration of indoor NO_2 with increasing height,

SQ4. Are the main sheds of the railway depots in this study well-mixed?

The presence of a NO_2 concentration gradient within all four depots indicate all of the main sheds of each of the 4 depots considered in this study, are not well-mixed.

SQ5. Are there seasonal variations in the indoor air quality within the Manchester Victoria train station of the study?

Seasonal variations were seen to have very little effect on air quality at the Manchester Victoria train station.

SQ6. What assumptions underpin the box model?

It assumes that the pollutant concentration is at steady-state conditions within the box, with the pollutant concentration, the same at all points within the box model, due to a well-mixed box.

SQ7. Is the concentration of NO_2 in the repair shed constant at all positions inside of the shed?

The concentration of NO_2 within the repair shed is not constant at all positions within the shed. This indicates that the repair shed is not well-mixed contravening the assumptions of the box model.

SQ8. Does the box model accurately predict the indoor NO_2 concentration in the repair shed at ground level?

The box model did not accurately predict the indoor NO_2 concentration in the repair shed at ground level. This can be attributed to evidence of poor mixing with the repair shed with noted spatial variations in the indoor NO_2 concentration. Consequently, with a poorly mixed repair shed, the externally provided estimation for the air extraction ventilation removal rate of 6 ACH was likely to be an overestimation and in reality, the air exchange rate was likely to be much lower than 6 ACH.

SQ9. How does the NO_2 indoor concentration vary with time within the Manchester Victoria train station?

The monthly NO_2 concentrations were near constant with changing season.

SQ10. Is there any indication of a NO_2 concentration gradient within the Manchester Victoria station?

There is evidence of a concentration gradient within the Manchester gradient, with increases in monthly NO_2 concentration with height.

SQ11: How does the NO_2 (nitrogen dioxide) and $PM_{2.5}$ indoor concentration vary with time within the repair shed of the Neville Hill railway depot?

SQ12: Is there a particular train type which contributes significantly to indoor air pollution within the repair shed of the Neville Hill railway depot?

The 170 DMU through statistical analysis was shown indicatively to be a significant contributor to indoor NO_2 concentrations within the repair shed of the Neville Hill depot. The 158 DMU was shown indicatively to be a significant contributor to indoor $PM_{2.5}$ concentrations within the repair shed of the Neville Hill depot.

SQ13: How do the transient NO_2 concentrations within the repair shed of Neville Hill compare against the UK's hourly NO_2 ambient air quality standard and with other studies of semi-enclosed environments dominated by rail emissions?

The transient hourly NO_2 concentrations basis reported several instances greater than the hourly NO_2 AQS of 200 µg m^{-3} with 25 exceedances above this standard over a short period of 9 days. With only 18 exceedances, allowable over a one year period, albeit in outdoor environments, if the NO_2 monitoring was continued over a longer period, a very significant number of exceedances above the hourly NO_2 AQS would likely be noted. However, given that the AQS only applies in outdoor environment, it must be stated that all of the key pollutants considered in this project, NO, NO_2, $PM_{2.5}$ and PM_{10} are within the UK legal requirements for indoor air pollution, governed by the HSE EH40 directive. When compared against other semi-enclosed rail studies, the transient hourly NO_2 concentrations were lower than other studies.

The 3 objectives of this study listed below have been addressed:

O1. To determine the parameters that affect air quality within UK railway depots and train stations where diesel trains are in operation.

O2. To measure the emission levels of Northern Rail trains in a working railway depot, and to compare this emission data against other vehicles.

O3. To assess the WTW (Well to Wheel) impacts of introducing alternative fuels into diesel-powered trains.

For O1, parameters have been identified that affect air quality within UK railway depots where diesel trains are in operation in Chapters 5 & 6. These include seasonal variations (Chapter 5 – section 5.3), indoor temperature (Chapter 5 – section 5.6) and train type (Chapter 5 – section 6.3). In terms of train stations, seasonal variations were found to have no effect on air quality within the Manchester Victoria station of this study (Chapter 6) and further work is required to determine what other parameters affect air quality within a station. For O_2, the emission levels of Northern trains in a working railway depot were determined in Chapter 4, and this was compared against emission data for similar power rated rail and road vehicles, within the same chapter. For O3, the WTW impacts of introducing alternative fuels into diesel-powered trains were also assessed in Chapter 4, with HVO and GTL discussed as detailed previously in the context of addressing the research questions.

The aim of this study has been covered in detail with the emissions of Northern Rail's fleet of DMU trains investigated (in Chapter 4) and their impact on air quality quantified (Chapters 5-6). The potential for alternative fuels such as GTL and HVO within these same DMUs were also covered within Chapter 4.

7.2 Impact of research

This research has built on the previous air pollution monitoring campaigns at London Paddington station and Birmingham New street station, and has extended the analysis included vertical static pollution measurements over a longer period of time to these two studies (Chong et al., 2015; Hickman et al., 2018b). The diffusion tube NO_2 concentration data from Manchester Victoria station between 2019-20 played a part in the installation of a new ventilation extraction system in the overbridge section connecting platforms 3 and 6 as pictured in Figure 7.1, which was installed in late spring 2020 after the diffusion tube monitoring concluded in November 2019 at the station. The data from the Neville Hill railway depot and the Heaton depot have led to positive discussions with Network Rail for a new ventilation extraction system to be procured.

The DMU emissions' data from Chapter 4 has been shared with the RSSB, who used this information anonymised within their T1187 report to better understand the real-world drive emissions at different notch rail power settings. As part of this an

acknowledgement was apportioned to the 'University of Leeds' in the T1187 report on p7 as seen in Figure 7.2 (Grennan-Heaven and Gibbs, 2020b). Throughout the project there has been positive discussions with the RSSB for their work in rail air quality and emissions research, with data shared for their T1187 project and support has been lent to their T1190 project on air quality in depots for their work at the Neville Hill railway depot. A paper has been internally drafted in an anonymised form of the Neville Hill railway depot's data, entitled 'Investigation of the impact of temperate gradients on indoor air quality within a railway depot.' As part of the future work, this draft paper, could be progressed further to completion, with suitable journals for this draft paper including:

1. International Journal of Environmental Research and Public Health
2. Proceedings of the Institution of Civil Engineers - Transport
3. Environmental Science and Technology
4. Atmospheric Environment
5. Environmental Pollution

Figure 7.1 New ventilation system at the Manchester Victoria station in the overbridge section

Acknowledgements

Technical data, support, advice and feedback was provided by these organisations and is gratefully appreciated.

Abellio	EMD	Network Rail
Angel Trains	EMR	Northern
Arriva	First Group	Porterbrook
Avanti West Coast	Freightliner	ScotRail
Bombardier	Grand Central	SNC-Lavalin
CAF	GWR	TransPennine Express
Chiltern	Hitachi	University of Leeds
Colas	Horiba	University of Loughborough
CrossCountry	Hull Trains	Wabtec
DB Cargo	MTU	

Figure 7.2 University of Leeds acknowledgement in T1187 RSSB report (Grennan-Heaven and Gibbs, 2020b)

7.3 Recommendations

There are a number of recommendations from this study:

1. Further research into the mixing behaviour within railway depots and stations, using CFD models, in conjunction with indoor air flow measurements.
2. Expand the temperature measurements within the Neville Hill's repair shed to investigate the presence of any stratification behaviour.
3. Conduct further exhaust emission measurements of the DMUs within the railway depot with applied load, to determine the individual notch emissions and corresponding factor. This could then be used to determine more accurate emission factors (in g/kWh).
4. Trial HVO or GTL within a DMU fleet vehicle and measure the changes in exhaust emission concentrations vs. low sulphur diesel, to see if the estimated reduction in source emissions correspond to measured exhaust measurements.
5. Extend the transient monitoring of NO_2 and $PM_{2.5}$ within the Neville Hill depot's repair shed to a period of 1 year, and determine local bias adjustment factors. From this, annual NO_2 and $PM2.5$ concentrations can be determined for comparison against the UK AQS. The relevant UK AQS are 200 µg m^{-3} hourly for NO_2 and 20 µg m^{-3} annually for $PM_{2.5}$.

7.4 Future work

There are number of areas which have not been covered in this work which would build on the air quality and emissions measurements conducted for this project. These include:

a) Alternative fuel testing on static trains within a railway depot

b) Alternative fuel testing on static trains using a load bank

This expands on research question 3: ‘What factors need to be considered when introducing alternative fuels into diesel-powered trains? Details of this are outlined in Appendix G.

In addition further work, can be done on more complex methods of regression analysis, for the variables affecting the concentration of indoor NO_2 obtained from the Neville Hill railway depot’s repair shed, expanding on research question 4. Random forests is one such method. Random forests uses a black-box type method to determine a relationship between the dependent variables and independent variables, and can be used for linear and non-linear relationships. Within R, either the ‘ranger’ or ‘random forests’ package can be used for random forests. Font et al., used the random forests method to determine which dependent variables contributed the most to the concentrations of NO_2 and $PM_{2.5}$ within the indoor train stations of London’s King’s Cross and Edinburgh Waverley (Font et al., 2020). Some R code has been included in the Appendix H, for how random forests may be utilised to apportion variable attribution for the indoor NO_x concentration data for Neville Hill railway depot, i.e. which variable has the most significant effect on indoor NO_x in this railway depot.

Appendix A Correspondence with DfT on UK rail fleet

Department for Transport

Department for Transport
Great Minster House
33 Horseferry Road
London
SW1P 4DR
Tel: 0300 330 3000

Web Site: www.gov.uk/dft

Our Ref: 370633

20 October 2021

Jason Ferns
Energy Building
University of Leeds
209 Clarendon Road
Leeds
LS2 9DT

By email: pmjf@leeds.ac.uk

Dear Mr Ferns,

Thank you for your enquiry of 23 October 2021 to the Department for Transport requesting information on diesel rolling stock operating on rail lines in the UK. Your correspondence has been passed to the Rail Passenger Services team to reply.

The following information is an approximate breakdown of diesel and electric powered units/locomotives in service with passenger operators in the UK (this does not include freight, heritage, other non-public service operators or units that are on test):

Type	
Bi-mode unit	5.8%
Diesel Multiple unit	30.2%
Electric multiple unit	61.6%
Diesel Loco	1.6%
Electric Loco	0.4%
Bi-mode Loco	0.4%

The owners of the diesel rolling stock would be best placed to answer queries in relation to the technical aspects of their fleets, details for the rolling stock owning companies can be found on the Office for Rail and Road (ORR) website at:
https://www.orr.gov.uk/about/who-we-work-with/industry/rolling-stock-companies

The Department has not published an updated version of the Rolling Stock Perspective, however other useful sources of information that are available in the public domain include:

Platform 5 Rolling Stock guides:
https://www.platform5.com/Catalogue/Modern-British-Railways/British-Railways-Locomotives-Coaching-Stock-2021-5LCS21 and the abc Rail Guide: http://www.crecy.co.uk/abc-rail-guide-2021

Thank you again for your enquiry and we hope that this information is helpful. We wish you every success with your PhD.

Yours sincerely,

Correspondence Team, Rail Passenger Services Directorate

Figure 7.3 Percentage composition of UK passenger rail fleet

Appendix B Train maintenance procedures

	VEHICLE MAINTENANCE INSTRUCTION	VMI 14X
northern	CLASS 14X PACER DMUs	Issue: 1 Revision: A Date: July 2005 **Job No: V*S 0020** **Page 1** of 1

JOB NO. V*S 0020

INITIAL TESTS

SAFETY CONDITION	
PRIMARY	ALL LIVE
ADDITIONAL	

SUMMARY
Initial test - Run engine and check engine, transmission and vehicle systems for unusual noises, leaks, damage etc

1. Start the engine locally.

2. Check the engine, transmission unit and vehicle systems for unusual noises, leaks, knocking and damage etc. Check for excessive smoke from the crankcase breather or lubricating oil being pressurised out of the oil filling system.

NOTE 1

Systems to include Air, Hydrostatic, Fuel, Coolant, Oil and Exhaust.

NOTE 2

Excessive oil being pressurised out of the oil filler or the crankcase breather can be caused by the engine oil level being above the full mark.

3. Stop the engines locally (B Side).

4. Repair or rectify minor defects or report to Team Leader.

Figure 7.4 Northern train maintenance procedure for initial tests during routine work

northern	VEHICLE MAINTENANCE INSTRUCTION	VMI 14X Issue: 1 Revision: A Date: July 2005 Job No: V*S 0021 Page 1 of 1
	CLASS 14X PACER DMUs	

JOB NO. V*S 0021

FINAL CHECKS - ENGINE, TRANSMISSION AND SYSTEMS

SAFETY CONDITION	
PRIMARY	ALL LIVE
ADDITIONAL	

SUMMARY
Final Checks - Run engine and check engine, transmission and vehicle systems for unusual noises, leaks etc. paying particular attention to items that have been disturbed. Recheck / Top up engine oil level.

MATERIALS			
ITEM	DESCRIPTION	QTY/VEH	BR CAT NO
1	Multigrade crankcase oil to BR Spec 669 (Bulk) (205 litres)		 027/020450 027/020452

1. Start the engine locally and run at idle for 5 minutes.

2. Check the engine, transmission unit and vehicle systems for unusual noises, leaks, knocking and damage etc. Check for excessive smoke from the crankcase breather or lubricating oil being pressurised out of the oil filling system.

NOTE 1

Systems to include Air, Hydrostatic, Fuel, Coolant, Oil and Exhaust.

3. In checking for leaks and defects pay particular attention to items that have been repaired or renewed.

NOTE 2

Excessive oil being pressurised out of the oil filler or the crankcase breather can be caused by the engine oil level being above the full mark.

4. Shut down the engines

5. If the engine oil and filters have been changed, allow 15 minutes for oil to drain back into the engine sump, recheck the engine oil level and fill to the 'FULL STOPPED' line (see Materials item 1) on the markings adjacent to the sight glass if required.

6. Repair or rectify minor defects or report to Team Leader.

Figure 7.5 Northern train maintenance procedure for final checks during routine work

northern	VEHICLE MAINTENANCE INSTRUCTION	VMI 14X Issue: 1 Revision: H Date: Sept 2013 **Job No: AZS 9300** **Page 1** of 2
	CLASS 14X PACER DMUs	

JOB NO. AZS 9300

AIR SYSTEM BUILD UP TEST

SAFETY CONDITION	
PRIMARY	ALL LIVE
ADDITIONAL	

SUMMARY
Carry out air build-up test.

SPECIAL TOOLS		
ITEM	**DESCRIPTION**	**BR CAT NO**
1	Test Gauge (0 - 10 bar)	

SPECIAL TOOLS		
ITEM	**DESCRIPTION**	**BR CAT NO**
1	Drain Cock Noise Baffle	-

1. Isolate the vehicle air system from all other vehicles.

2. At each reservoir, fit a Drain Cock Noise Baffle (see Special Tools item 1) to the exhaust of the drain cock. Drain all the air out of the system including all reservoirs.

3. Close each drain cock and remove the noise baffle.

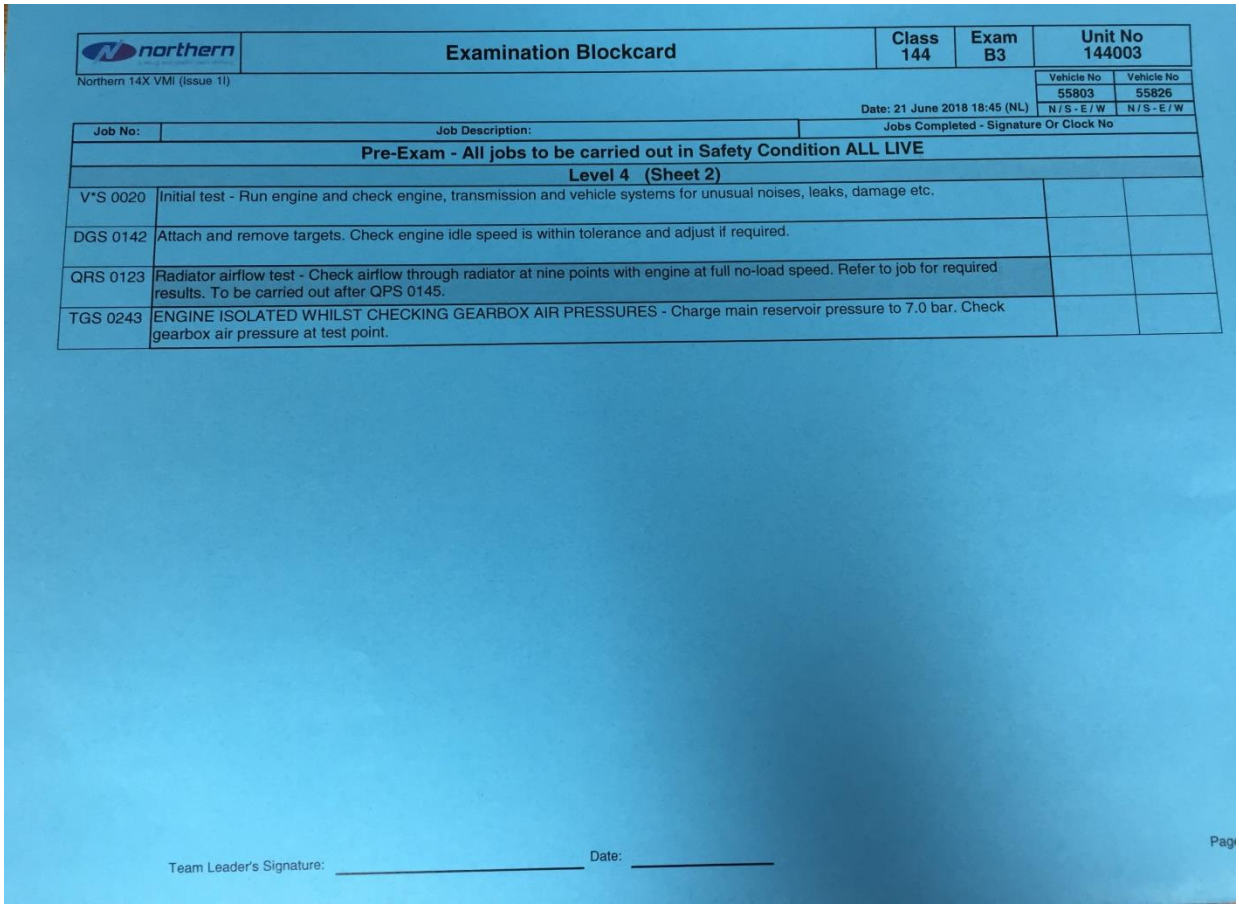
4. Attach a test gauge (see Special Tools item 1) to the main reservoir pipe test point or to the emergency connection.

5. Start the engine locally. Turn on the compressor speed up switch and check the following:-

   5.1 The brake cylinder pressure rises simultaneously with the main reservoir pressure. If the brake cylinder pressure does not start to rise before the main reservoir pressure reaches 1.5 bar, examine the main reservoir and brake air system for defects, in particular the Brake Supply Reservoir Check Valve, and repeat this test.

   5.2 The time taken to fully charge the air system to 7.6 bar or until the compressor unloader/governor operates to unload the compressor. The time taken should be no more than 6 minutes, if it is greater, then check the air system for defects and repeat this test.

Figure 7.6 Northern train maintenance procedure for air build-up checks during routine work



northern

Examination Blockcard

Class	Exam	Unit No
144	B3	144003

Northern 14X VMI (Issue 1I)

Vehicle No	Vehicle No
55803	55826
N / S - E / W	N / S - E / W

Date: 21 June 2018 18:45 (NL)

Job No:	Job Description:	Jobs Completed - Signature Or Clock No	
	Pre-Exam - All jobs to be carried out in Safety Condition ALL LIVE		
	Level 4 (Sheet 2)		
V*S 0020	Initial test - Run engine and check engine, transmission and vehicle systems for unusual noises, leaks, damage etc.		
DGS 0142	Attach and remove targets. Check engine idle speed is within tolerance and adjust if required.		
QRS 0123	Radiator airflow test - Check airflow through radiator at nine points with engine at full no-load speed. Refer to job for required results. To be carried out after QPS 0145.		
TGS 0243	ENGINE ISOLATED WHILST CHECKING GEARBOX AIR PRESSURES - Charge main reservoir pressure to 7.0 bar. Check gearbox air pressure at test point.		

Team Leader's Signature: _____ Date: _____

Pag

Figure 7.7 Typical Northern train maintenance procedure for B exam (heavy maintenance)

Appendix C Correspondence with SMG-Europe on Manchester Victoria ventilation

From: Dave Batty <dave.batty@smg-europe.com>

Sent: Thursday, January 24, 2019 12:22 pm

To: Jason Ferns

Cc: Will Marsden; John Murphy

Subject: RE: Manchester Victoria ventillation extraction system

Jason

Answers below

Regards

David Batty

SMG-Europe

Assistant FM Director

T 01619502071

F 01619507007

M 07773282914

Figure 7.8 Correspondence with SMG-Europe on Manchester Victoria ventilation system - p1

Hi Dave,

I have just received your details from your colleague, Karl. I am a student from the University of Leeds investigation the air pollution at Manchester Victoria in partnership with Northern Rail.

Can you provide the following information on the ventillation extraction system in place at Manchester Victoria:

1.Is the ventillation system currently switched on?

yes

2.What are typical times the ventillation system is switched on? (From briefly walking around, I can not hear any audible hum for the extraction roof panels)

24 hour operation

3. Are the ventillation ducts cleaned periodically? To ensure that any soot/oil does not clog up the ventillation shaft?

No not possible to clean the ducts without a track possession, however the control system and fans are accessible and maintained

4. Does the ventillation system have a variable control on the amount that can be extracted? e.g. 25% extraction, 50% extraction, 100% extraction by adjusting the extraction velocity.

No, the system runs at 100% if required, there are a number of different systems across the different platform each with their own sensor

5. Does the control panel for extraction system record the extraction flow rate? m3/h of air?

No, it only logs the number of hours the system has run for

I have had a look at the control panel for the extraction system via Northern's station team leader. Would it be possible to make someone available to illustrate how the ventillation extraction control panel works?

Sensors on the platform, determine if the air quality requires the system to run, if required the system runs at 1005 until the sensors clear the requirement, and the hours run are logged on the system, quite straight forward and simple

Figure 7.9 Correspondence with SMG-Europe on Manchester Victoria ventilation system – p2

Appendix D Correspondence from Network Rail on trigger alarms for Manchester Victoria ventilation

From: Gee Peter [mailto:Peter.Gee@networkrail.co.uk]
Sent: 22 August 2019 15:19
To: John Murphy
Cc: Lydia Hayes; Ellams Robert; Lewis Alex; Quaiyoom Azhar; Griffin Sinead
Subject: RE: Manchester Victoria Station. Platform Ventilation Systems.
Importance: High

Hi John,
I've emailed you a few times now, but not received a reply.
As stated previously, I'm a little confused.....

On your attached (Most Recent)Safety Gas Detection Service Record 6135, dated **7th June 2019** (Attached), the Alarm levels are shown as:-

Gas Measured	Carbon Monoxide ppm	NO2 ppm	Co2 ppm
1st Alarm Level	10	0.5	700
2nd Alarm level	20	2.5	1050

However on the previous Safety Gas Detection Service Record 5090, dated **29th October 2018** (Attached), the Alarm levels are also shown as:-

Gas Measured	Carbon Monoxide ppm	NO2 ppm	Co2 ppm
1st Alarm Level	10	0.5	700
2nd Alarm level	20	2.5	1050

These Alarm level set points appear to be identical.

We were expecting to see something more like this:-

Gas Measured	Carbon Monoxide ppm	NO2 ppm	Co2 ppm
1st Alarm Level	5	0.25	350
2nd Alarm level	10	1.25	525

Have these set points been changed? – Or is the above due to a typographical error?

Many Thanks,
Regards,
Peter.

Peter Gee. - I.Eng. ACIBSE | Asset Management Buildings LNW | Asset Engineer (Building Services)
Network Rail | Square One | 4 Travis Street | Manchester | M1 2NY
Mobile: +44 (0) 7701052334
Peter.Gee@networkrail.co.uk
www.networkrail.co.uk

Planned Leave:-

1

Figure 7.10 Correspondence from Network Rail on Manchester Victoria trigger alarms for ventilation system

Appendix E Price data for GTL and HVO

Hi Jason

Thanks for your e-mail we can supply both Shell GTL and HVO both will be dyed red for duty purposes and can be used on trains, current prices are as below. The Shell GTL can be completely offset for an extra 1p per litre see attached about Carbon offsetting.

Shell GTL Off Road – 47.50 pence per litre

HVO Off Road – 72.50 pence per litre

If you need any further information please do not hesitate to contact me.

Kind regards

Malcolm

Malcolm Dennis
Manager Speciality Fuels and Services

Certas Energy UK Limited
Westerleigh Terminal
Oakley Green

Figure 7.11 GTL and HVO price data

Appendix F NO_2 diffusion tube concentration data without relative bias

Table 7.1 Annual NO^2 concentration data for Allerton railway depot without relative bias correction

	Time Weighted Annual Mean (µg m^{-3})	
Diffusion Tube ID	**2018 Annualised**	**2019 Annualised**
Road 1 Centre	41.9	38.7
Road 3 Centre	-	40.5
Road 4 Centre	41.5	49.8
Road 5 Centre	40.0	55.3
Allerton End Road 1	40.7	52.9
Allerton End Road 3	39.7	57.0
Allerton End Road 4	36.6	36.1
Allerton End Road 5	38.1	-
Hunts Cross End Road 1	42.1	54.6
Hunts Cross End Road 3	43.0	
Hunts Cross End Road 4	47.8	39.7
Hunts Cross End Road 5	51.0	42.8
Road 4 Centre 3.2m	44.5	52.5
Road 4 Centre 4.9m	32.3	55.5
Average at ground level of 1.6m		

Table 7.2 Annualised indoor NO_2 concentration data for the Heaton depot main shed without relative bias correction

Diffusion Tube ID	**2018 Time Weighted Annual Mean (µg m^{-3})**
Road 1 Centre	204.8
Road 1 North	187.2
Road 2 North	157.8
Road 3 North	169.3
Road 4 North	164.1
Road 5 North	118.6
Road 6 Centre	86.2
Road 7 Centre	87.5
Road 7 South	105.0
Road 6 South	103.4
Road 5 South	90.3
Road 4 South	76.0
Road 3 South	86.6
Road 2 South	107.5
Road 1 South	101.8

Road 4 Centre 5m	335.0
Road 4 Centre 2.5m	259.5
Road 4 Centre 1.6m	144.2
Average at ground level of 1.6 m	

Table 7.3 Annualised time weighted annual NO_2 concentrations for the Neville Hill railway depot without relative bias correction

Diffusion Tube ID	**2018 Time Weighted Annual Mean (µg m^{-3})**	**2019 Time Weighted Annual Mean (µg m^{-3})**
Road 1 East	58.4	96.4
Road 1 Centre	60.3	90.7
Road 1 West	57.0	102.6
Road 2 East	60.6	95.0
Road 2 Centre	63.2	82.5
Road 2 West	62.2	69.5
Road 3 East	56.2	97.2
Road 3 West	73.6	99.3
Road 4 East	61.4	97.9
Road 4 West	61.0	87.1
Road 5 East	63.1	99.3
Road 5 Centre	79.1	123.3
Road 5 West	60.6	89.0
Road 3 Centre (5.2m)	91.3	-
Road 3 Centre (4.3m)	75.3	-
Road 3 Centre (3.2m)	64.9	-
Road 3 Centre (2.6m)	64.5	-
Road 3 Centre (1.3m)	63.2	-
Average at ground level of 1.6 m		

Table 7.4 Annualised time weighted annual NO_2 concentrations for the Newton Heath railway depot without relative bias correction

Diffusion Tube ID	**2018 Time Weighted Annual Mean (µg m^{-3})**
Road 4 Centre 5.6m	154.2
Road 4 Centre 2.8m	74.3
Road 4 Centre 1.6m	63.9
Road 7 Centre 1.6m	57.2
Road 10 Centre 1.6m	55.7
Road 4 Manchester End 1.6 m	75.4
Road 5 Manchester End 1.6m	84.7
Road 6 Manchester End 1.6m	85.1
Road 7 Manchester End 1.6m	67.4
Road 8 Manchester End 1.6m	73.1
Road 10 Manchester End 1.6m	62.0
Road 4 Oldham End 1.6m	42.3
Road 5 Oldham End 1.6m	73.9
Road 6 Oldham End 1.6m	65.3

Road 7 Oldham End 1.6m	54.0
Road 8 Oldham End 1.6m	55.0
Road 9 Oldham End 1.6m	-
Road 10 Oldham End 1.6m	58.0
Average at ground level	

Table 7.5 Annualised time weighted annual NO_2 concentrations for the Manchester Victoria station without and with relative bias correction

Diffusion Tube ID	**2019 Annual Mean without relative bias correction (µg m^{-3})**	**2019 Relative Bias corrected Annual Mean (µg m^{-3})**
Platform 1 West 2.5m	49.2	40.4
Platform 1 Centre 2.5m	52.3	42.9
Platform 1 East 2.5m	47.1	38.6
Platform 3 Central 2.5m	68.8	56.4
Platform 3 West 2.5m	52.6	43.1
Platform 3 East	69.9	57.3
Overbridge platform 3, 2.7m	241.5	198.1
Overbridge Central platform 4, 2.7m	263.4	216.0
Overbridge Platform 5, 2.7m	202.5	166.0
Platform 6 East 2.5m	81.0	66.5
Platform 6 Central 2.5m	108.8	89.2
Platform 6 Entrance 2.7m	292.2	239.6
Platform 4 East 2.5m	79.0	64.8
Platform 4 Central 2.5m	79.0	64.7
Platform 2/3 Central 2.5m		-
Platform 2/3 West 2.5m	53.1	43.5
Concourse Beerhouse Bar	47.3	38.8
Average at 2.5 m		

Appendix G Multivariate linear regression R code

NOx

```
rm(list=ls())
setwd("c:/Users/pmjf/Desktop/Horizontal data template/Regression/Multivariate linear regression - R")
pdata<-read.csv("hourlyNOX.csv",header=TRUE)
names(pdata) <- c("NOX","N150","N155","N158","N170","Te")
fit <- lm(NOX ~ N150 + N155 + N158 + N170 + Te, data=pdata)
summary(fit)
plot(fit)
plot(pdata[,5],pdata[,1],xlab="N170",ylab="NOX (ppm)",lwd=1)
abline(0.2675,0.1118)
#with(pdata, plot(N170, NOX))
#abline(fit)
#https://stackoverflow.com/questions/5587676/pull-out-p-values-and-r-squared-from-a-linear-regression
#anova(fit)
#p values
summary(fit)$coefficients[,4]
#pdp1 <- plotPartial(pd)
#MLR<-partial(fit, pred.var = "N170", plot = TRUE, rug = TRUE, plot.engine = "ggplot2")
```

$PM_{2.5}$

```
rm(list=ls())
setwd("c:/Users/pmjf/Desktop/Horizontal data template/Regression/Multivariate linear regression - R")
pdata<-read.csv("hourlyPM25.csv",header=TRUE)
names(pdata) <- c("PM25","N150","N155","N158","N170","Te")
fit <- lm(PM25 ~ N150 + N155 + N158 + N170 + Te, data=pdata)
summary(fit)
plot(fit)
with(pdata, plot(N170, PM25))
abline(fit)
#https://stackoverflow.com/questions/5587676/pull-out-p-values-and-r-squared-from-a-linear-regression
anova(fit)
#p values
summary(fit)$coefficients[,4]
```

Appendix G Alternative fuel testing with PEMS

This section outlines a two possible options for conducting an alternative fuel test in a railway environment. Option 1 is by the use of on-board PEMS system fitted to a moving single carriage train. Option 2 is through the use of a load bank connected to a single engine removed from a single train carriage.

Option 1: Alternative fuel testing on static trains within a railway depot

It is proposed as a future plan to trial 1 alternative fuel in a single trial in one chosen DMU carriage. The train a possible 14X unit will be moved from the repair shed to the fuel tanking shed in order to remove all of the diesel within 1 carriage of the train and refuelled with an alternative fuel of HVO to full engine capacity. The alternative fuel chosen is HVO (Hydrogenated Vegetable Oil which is a drop-in fuels and require no engine modification to operate within the train fuelling tank.

Draining of the diesel fuel in the tank could be removed with existing facilities in place within the fuel mixing shed. In the event, that no facilities are available for draining diesel at the depot, a reverse flow pump will be used to extract the diesel into the diesel storage tanks within the fuel mixing shed. The HVO will be stored in steel drums. The fuel could be then transported into an IBC 1000 litre tank if necessary and then pumped from the IBC tank into the train. The refuelled carriage with HVO will be moved from the fuel tanking shed back to the repair shed for exhaust testing.

The emission equipment will be reattached over a period of 4-5 hours. The emission test will last between 15-30 mins with 1-2 min one each notch power setting from notch 0(idle) to max power. Following the conclusion of the alternative fuel tests, the carriage will be moved from the repair shed back to the fuel tanking shed. The HVO will be drained either directly to the HVO fuel drum or to an intermediate IBC tank.

The Horiba OBS-One, shown in Figure 7.12, is one such equipment that could be used to monitor a set of different exhaust emissions, including CO, CO_2, NO, NO_2, NO_x and selected hydrocarbons, could be leased/rented from Horiba for the emission testing of the alternative fuel.

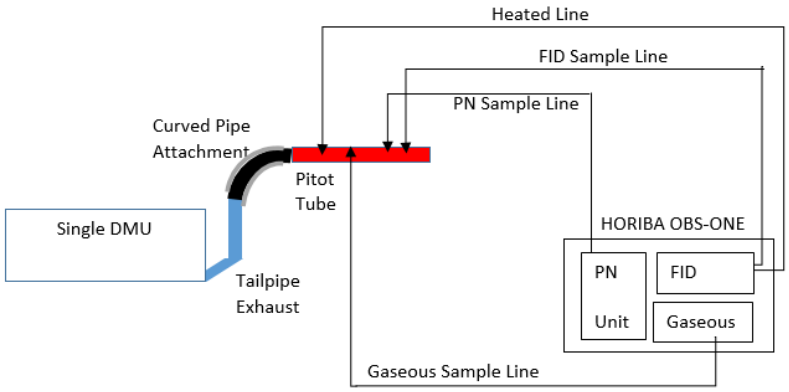


Figure 7.12 Horiba OBS-One set-up for alternative fuel testing

Overall plan for tests

Day 1 – Installation of exhaust emission equipment (2 hours)

Day 1 – Power up emission equipment and left to warm up (4 hours)

Day 1 – Exhaust emission test if possible (0.5 hour)

Day 2 – Move train from repair shed to fuel tanking shed (1 hour)

Day 2 – Drain all diesel from one carriage (1 hour)

Day 2 – Refuel with alternative fuel of HVO (1 hour)

Day 2 – Move train from fuel tanking shed to repair shed (0.5 hour)

Day 2 - Installation of exhaust emission equipment (2 hours)

Day 2 – Power up emission equipment and left to warm up (4 hours)

Day 2 – Alternative fuel of HVO exhaust emission test (0.5 hour)

Day 2 – Move train from repair shed to fuel tanking shed (0.5 hour)

Day 2 – Drain all HVO from the one carriage (1 hour)

Option 2: Alternative fuel testing on static trains using a load bank

Test bed trials of HVO fuel could be undertaken within one of the Cummins engine utilised in trains at the LH facility in Burton-on-Trent. The Cummins engines available are the NTA855R1, NTA855R3, NTA855R5 and the LTA-10R. Arrangements with LH would need to be made, to see which of these engines would be available for testing, and not to disrupt LH's commercial contract work. Some form of exhaust emission equipment will be required to monitor the effects of using a biofuel such as HVO, in comparison to standard ULSD diesel currently used in the trains. The FTIR,

shown in Figure 7.1, is one such equipment that could be used to monitor a set of different exhaust emissions, including CO, CO_2, NO, NO_2, NO_X and selected hydrocarbons. Alternatively, the Horiba OBS-One could be leased/rented from Horiba for the emission testing of the alternative fuel, as shown in Figure 7.2

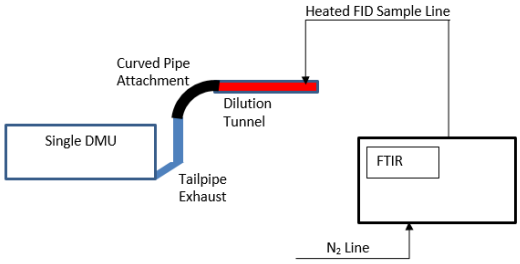


Figure 7.13 FTIR set-up for alternative fuel testing

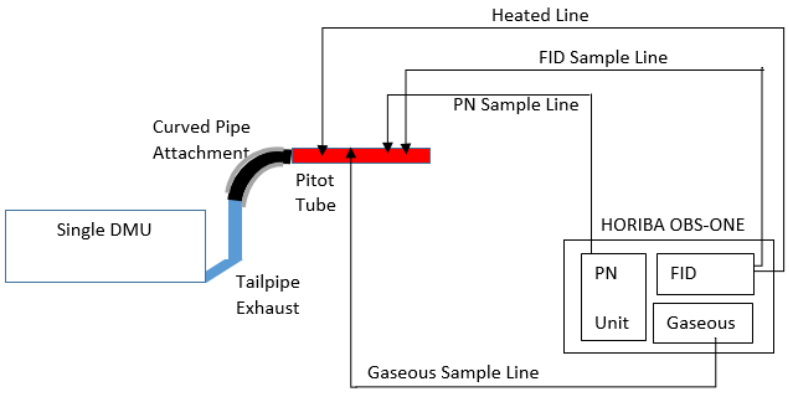


Figure 7.14 Horiba OBS-One set-up for alternative fuel testing

Appendix H Random forests R code

NOx

```
rm(list=ls())

pdata<-read.csv("3minH.csv",header=TRUE)

str(pdata)

outcome <- "NOX"

# The input variables

(vars <- c("N144","N153","N155","N158","N170"))

# Create the formula string for NOX rented as a function of the inputs

fmla <- paste(outcome, "~", paste(vars, collapse = " + "))

# Load the package ranger

library(ranger)

# Fit and print the random forest model.

(pdata_rf <- ranger(fmla,

                    pdata,

                    num.trees = 500,

                    respect.unordered.factors = "order",seed = set.seed(1)

                    ))

(model <- ranger(fmla,

                 pdata,

                 num.trees = 500,

                 respect.unordered.factors = "order",seed = set.seed(1)

))

library(dplyr)

library(ggplot2)

pdata$pred <- predict(model,pdata)$predictions

pdata %>%

  mutate(residual = NOX - pred)  %>%        # calculate the residual
```

```
  summarize(rmse  = sqrt(mean(residual^2))) # calculate rmse


# Plot actual outcome vs predictions (predictions on x-axis)
ggplot(pdata, aes(x = NOX, y = pred)) +
  geom_point() +
  geom_abline()
fit1 <- lm(pred ~ NOX, data = pdata)
library(mblm)
V1 <- NOX ~ N144
V2<-NOX~N153
V3<-NOX~N155
V4<-NOX~N158
V5<-NOX~N170
A<-mblm(V1,pdata,repeated=TRUE)
B<-mblm(V2,pdata,repeated=TRUE)
C<-mblm(V3,pdata,repeated=TRUE)
D<-mblm(V4,pdata,repeated=TRUE)
E<-mblm(V5,pdata,repeated=TRUE)

library(rsample)
split <- initial_split(pdata, prop = 0.7, strata = "NOX")       #this splits the raw data into two datasets with 70% of rows in one, 30% in 2nd data sheet

pdata_train  <- training(split)                 #1st split data sheet is training datasheet
pdata_test   <- testing(split)
summary(pdata)
rf_impurity <- ranger(
  formula = fmla,
  data = pdata_train,
```

```
  num.trees = 500,
  mtry = 4,
  min.node.size = 1,
  sample.fraction = .80,
  replace = FALSE,
  importance = "impurity_corrected",
  respect.unordered.factors = "order",
  verbose = FALSE,
   seed  = 123
)

importance_pvalues(rf_impurity, method = "janitza")
# re-run random forests model with permutation-based variable importance
rf_permutation <- ranger(
  formula = fmla,
  data = pdata_train,
  num.trees = 500,
  mtry = 4,
  min.node.size = 1,
  sample.fraction = .80,
  replace = FALSE,
  importance = "permutation",
  respect.unordered.factors = "order",
   seed  = 123
)
importance_pvalues(rf_permutation, method = "altmann", formula = fmla, data = pdata_train)
(model2 <- ranger(fmla,
                  pdata_train,
```

```
            num.trees = 500,
            respect.unordered.factors = "order",seed = set.seed(1)
))
actual <- pdata_train$NOX
predicted <- unname(predict(model, pdata))

pdata_train$pred <- predict(model,pdata_train)$predictions
pdata_train %>%
  mutate(residual = NOX - pred)  %>%        # calculate the residual
  summarize(rmse  = sqrt(mean(residual^2))) # calculate rmse

# Plot actual outcome vs predictions (predictions on x-axis)
ggplot(pdata_train, aes(x = NOX, y = pred)) +
  geom_point() +
  geom_abline()
fit2 <- lm(pred ~ NOX, data = pdata_train)
p1 <- vip::vip(rf_impurity, num_features = 5, bar = FALSE)
p2 <- vip::vip(rf_permutation, num_features = 5, bar = FALSE)
plot(p1)
plot(p2)
gridExtra::grid.arrange(p1, p2, nrow = 1)
#https://bgreenwell.github.io/pdp/articles/pdp.html
library(h2o)
h2o.no_progress()
h2o.init()
y <- "NOX"
x <- setdiff(names(pdata_train), y)
```

```
# turn training set into h2o object
train.h2o <- as.h2o(pdata_train)

# hyperparameter grid
hyper_grid.h2o <- list(
  ntrees      = seq(100, 500, by = 100),
  mtries      = seq(1, 5, by = 1),
  sample_rate = c(.5, .6, .70, .80)
)

# build grid search
grid <- h2o.grid(
  algorithm = "randomForest",
  grid_id = "rf_grid",
  x = x,
  y = y,
  training_frame = train.h2o,
  hyper_params = hyper_grid.h2o,
  search_criteria = list(strategy = "Cartesian")
)

# collect the results and sort by our model performance metric of choice
grid_perf <- h2o.getGrid(
  grid_id = "rf_grid",
  sort_by = "mse",
  decreasing = FALSE
)
print(grid_perf)
```

```
library(pdp)
set.seed(123)  # for reproducibility
randomforest_rf <- randomForest(NOX ~ N144 + N153 + N155 + N158 + N170, data = pdata, importance =
TRUE)
vip(randomforest_rf, bar = FALSE, horizontal = FALSE, size = 1.5)
pd <- partial(randomforest_rf, pred.var = c("N170", "NOX"))

# Default PDP
pdp1 <- plotPartial(pd)
partial(randomforest_rf, pred.var = "N170", plot = TRUE, rug = TRUE,
        plot.engine = "ggplot2")
pd<-partial(randomforest_rf, pred.var = "N170", grid.resolution = 20)
plotPartial(pd, xlab="N170",ylab="NOX",lwd=1)
partial(randomforest_rf, pred.var = "N158", plot = TRUE, rug = TRUE,
        plot.engine = "ggplot2")
pd<-partial(randomforest_rf, pred.var = "N158", grid.resolution = 20)
plotPartial(pd, xlab="N158",ylab="partial dependency:NOX",lwd=1)
partial(pdata_train,
        pred.var = c("N170", "NOX"),
        trim.outliers = TRUE, chull = TRUE, parallel = TRUE,
        grid.resolution = 30,  paropts = list(.packages = "ranger"))
partial(rf_impurity, pred.var="N170", paropts = list(.packages(ranger)))
pd1<-partial(rf_impurity, pred.var="N170", paropts = list(.packages(ranger)))
plotPartial(pd1, xlab="N170",ylab="partial dependency: NOX",lwd=1)
pd2<-partial(rf_impurity, pred.var="N158", paropts = list(.packages(ranger)))
plotPartial(pd2, xlab="N158",ylab="partial dependency: NOX",lwd=1)
plotPartial(rf_impurity, pred.var="NOX", paropts = list(.packages(ranger)))
plot(pdata[,6],pdata[,1])
```

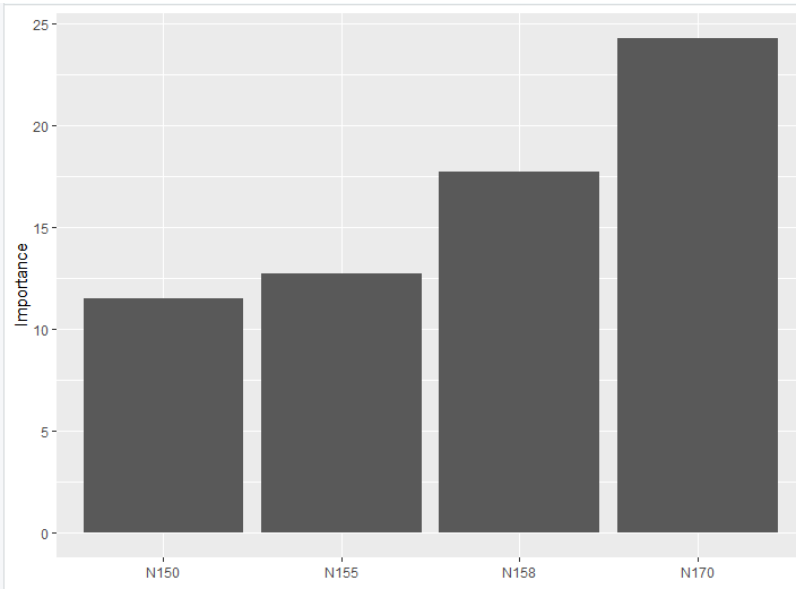


Figure 7.15 A typical variable importance plot generated using the random forests code in R

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