SUSTAINABLE DEVELOPMENT

RSSB A Better, Safer Railway

CLEAR: Performance Requirements and Testing Protocols for Emissions Mitigations

Review of emissions mitigation measures and retrofit approval schemes

T1235

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Executive Summary

Emissions of nitrogen oxides (NOx) and particulate matter (PM) from diesel rolling stock have been found to result in poor air quality on different parts of the GB rail network, including in enclosed stations and on-board certain rolling stock. In order to ensure that appropriate and effective mitigation measures are adopted, this project aims to establish a test protocol to assess the emissions benefits of various retrofit options for diesel rolling stock in a consistent manner and under test conditions which are representative of real-world usage. This protocol will provide the necessary level of confidence that emissions benefits will be achieved.

This review provides key background and a foundation for development of the testing protocol, which will be described in later reports. This document is aimed at providing academics and researchers with up-to-date knowledge in this area, and at rail industry technical staff and mitigation solution developers and manufacturers who will want to understand the basis for the planned protocol, as well as providing rail industry leaders and decision makers and with the background and learnings for how a GB retrofit approval programme should be structured and operated.

The planned testing protocol will be aimed at 'on-engine' retrofit mitigation solutions. However, 'off-engine' measures, including filtration devices, green walls and screens, may be able to address emissions once they have left the train. A separate review of such measures and their effectiveness is presented here, along with key recommendations on issues for the rail industry to consider when evaluating these types of measures.

The rail industry Air Quality Strategic Framework, which was published by RSSB in 2020, recommended developing a hierarchy of mitigation options based on cost, benefit and risk so that the emissions value of each mitigation option is fully understood. To avoid challenges associated with accessing the intellectual property and confidential business information of manufacturers and providers of retrofit mitigation solutions, it will be necessary to evaluate the effectiveness of different solutions in real world use using a standardised testing protocol that ensures testing data is consistent and comparable.

An approach that considers multiple engine mode points and the time spent at these mode points (i.e. the drive cycle) that reflects real world services for different rolling stock types will allow an understanding of emissions and expected reductions in key locations and parts of the drive cycle, such as idling in enclosed stations. Such data would allow the expected reductions in all parts of the drive cycle to be calculated. Collecting such data at this level will also avoid problems whereby the current non-road mobile machinery (NRMM) regulatory drive cycle places limited emphasis on idle. Importantly, there will be a need to understand how these characteristics change after the mitigation solution has been applied. Different mitigation solutions can be expected to require new mode test points to accurately reflect the new operating conditions (e.g. a new engine) and/or result in new drive cycles (e.g. a hybrid raft solution may result in

more time in higher engine powers but may also result in the engine not being used at all in key areas such as large, enclosed stations).

A range of current and under-development retrofit solutions that have the potential to mitigate emissions from GB rolling stock were reviewed. Characteristics assessed included potential impacts on NOx and PM emissions, fuel use and CO_2 emissions, typically fitted compliant rail engines, costs per DMU vehicle or locomotive, and whether installation of the solution would result in changes to the mode test points or their weightings (i.e. the drive cycle). For each major GB rolling stock class for which retrofits can realistically be considered, the suitability of each mitigation solution was considered, including whether NOx and/or PM emissions are reduced across all operations as well as within stations, availability of hardware, operational practicability and technical feasibility.

A survey of processes and programmes for the independent approval of retrofit emissions control systems covering rail, road transport, marine transport, construction and non-road mobile machinery (NRMM) was carried out. The programmes considered were:

- The United Nations Economic Commission for Europe R132 certification scheme
- The Clean Vehicle Retrofit Accreditation Scheme
- The Greater London Authority (GLA) construction equipment scheme
- US Environment Protection Agency (EPA) retrofit requirements for rail
- the US EPA National Emission Standards for Hazardous Air Pollutants (NESHAP) for reciprocating internal combustion engines (RICE)
- US EPA retrofit requirements for marine engines
- Various US state and local schemes.

Key learnings that will be relevant to development of a GB rail approval scheme include:

- A 'one size fits all' approach is not suitable for the range of NRMM activities; a sector-based approach can be more effective
- Testing protocols and other technical requirements for retrofits should be as robust as possible
- Emissions durability, i.e. the length of time for which an emissions reduction remains effective, has a large, mostly hidden impact on real-world emissions
- While reductions over time in US certification requirements appear smaller compared to European emissions standards, the real-world impact is much greater since the US approach pays much closer attention to actual drive cycles and real-world emission over the working life of the engine
- A greater cumulative impact on emissions can be achieved by retrofitting older existing engines where practical rather than making limited improvements to newer rolling stock that already have comparatively low emissions

- For retrofit kits, it is important to carefully specify parts (and designs) so *what was tested* is *what is supplied*
- The US rail approach is not just focused on direct emission reductions from mitigation solutions but also encourages emissions reduction at low engine powers due to better efficiency
- Mandated retrofits in the US for stationary reciprocating internal combustion engines focused on reasonably sized and easy reductions under a wide range of conditions and not on a target percentage or metric. Since known, robust technologies were used no end-user testing was required.
- The California Air Resources Board has enabled a number of initiatives, including funding research and development to assess emissions reductions and reliability of mitigation solutions. Long-term real-world usage trials can identify issues before large-scale deployment.

An emissions mitigation approval scheme for GB rail should include the following attributes:

- It needs to be able to assess emissions before and after installation for all realistic mitigation measures
- It should be based on real world drive cycles that reflect the expected conditions experienced by particular rolling stock on relevant services
- Such drive cycles may change substantially as a result of the installation of the mitigation solution, for instance more time in higher engine powers when the engine is running but also significant time when the engine is shut off. Sufficient information (at multiple test points) should be collected to ensure the full emissions reductions can be modelled and understood.
- The weighting maths used in US Rail and Euro VI Heavy Duty Road emission standards should be used to ensure the time in and emissions from idle are understood and addressed
- It should not be dependent on a single metric (e.g. g/kWh) but require the consideration and evaluation of individual mode test points.

This report provides the foundation for development of a testing protocol for retrofit emissions mitigation options for diesel rolling stock. The testing conditions to assess the emissions benefits of mitigation options will next be established as the test protocol is developed, along with identification of the performance requirements for different retrofit emissions mitigation options. Subsequent outputs of this project will include a protocol document and methodology report.

"On-engine" or "on-traction" measures are the main focus of this project. However, other, "off-engine", measures including keeping staff and passengers away from sources of emissions, passively or actively ventilating emissions, and treating or mitigating rail emissions after they have left the train. Such measures may be helpful in addressing concentrations of air quality pollutants within enclosed station environments. A range of such “off-engine” measures were reviewed and the following characteristics assessed:

- Effectiveness of reduction in exposure to air quality pollutants
- Scalability to rail
- Applicability
- Commercial feasibility
- Long term sustainability
- Operational feasibility & technical practicability
- Customer perspective.

A particularly challenging issue is scalability of solutions to meaningfully address the volume of air and the pollution it contains within a typical enclosed station. Many solutions are able only to affect concentrations within a limited area (5-10 m of a unit), and independent “before and after” studies of these types of measures are very sparse. Other solutions such as platform edge doors may be too costly and present a poor customer image. Improvements in natural ventilation, such as reopening roof gaps, may well be the most effective. A list of key questions for rail industry members to critically assess the effectiveness and suitability of off-engine mitigation products and solutions is provided.

Abbreviations

APA	Air Pollution Abatement
AQ	Air quality
AQEG	Air Quality Experts Group
CARB	California Air Resources Board
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CFD	Computational fluid dynamics
CVRAS	Commercial Vehicle Retrofit Approval Scheme
DOC	Diesel Oxidation Catalyst
DPF	Diesel particulate filter
DPS	Depot protection system
DMU	Diesel multiple unit
ECA	Emission Control Area
ECU	Engine control unit
EGR	Exhaust gas recirculation
EIC	Environmental Industries Commission
EPA	Environmental Protection Agency
ESP	Electrostatic precipitator
EST	Energy Savings Trust
GLA	Greater London Authority
GWR	Great Western Railway
HC	Hydrocarbons
HD	Heavy duty
HVAC	Heating, ventilation and air conditioning
HEPA	High efficiency particulate air
ISO	International Standards Organisation
IAQM	Institute of Air Quality Management
LEZ	Low emissions zone
LNER	London North Eastern Railway
LowCVP	Low Carbon Vehicle Partnership
LPG	Liquid petroleum gas
MARPOL	International Convention for the Prevention of Pollution from Ships
NESHAP	National Emission Standards for Hazardous Air Pollutants
NO	Nitric oxide

NO_2	Nitrogen dioxide
NOx	Nitrogen oxides
NRMM	Non-road mobile machinery
PAH	Polycyclic aromatic hydrocarbons
PM	Particulate matter
$PM_{2.5}$	Particular matter less than 2.5 micrometres in diameter
PM_{10}	Particular matter less than 10 micrometres in diameter
PED	Platform edge door
RICE	Reciprocating internal combustion engines
SAGE	Scientific Advisory Group for Emergencies
SALSCS	Solar-Assisted Large-Scale Cleaning System
SCR	Selective catalytic reduction
SOx	Sulphur oxides
TiO_2	Titanium dioxide
UNECE	United Nations Economic Commission for Europe
ZEMO	Zero Emissions Mobility (Partnership)

1 Introduction

1.1 Context

RSSB's Air Quality Strategic Framework, which was published in June 2020, details a series of recommendations to achieving air quality improvements in the rail sector through monitoring, modelling, and mitigation (Rail Safety and Standards Board, 2020). One of these recommendations is to

> *"Develop a hierarchy of mitigation options based on cost, benefit and risk so that the emissions value of each mitigation option is fully understood"*

The T1235 project 'Performance requirements and testing protocols for emissions mitigations' is part of the RSSB Clean Air Research (CLEAR) programme. This project aims to address this particular recommendation as laid out in the Framework by providing a consistent method for GB rail to effectively and objectively assess the impact of various mitigation options.

RSSB is developing an air quality monitoring network for rail costing £4.5 million which will provide an enhanced understanding of air quality challenges and their causes across the GB rail network. Attention on potential mitigation options that can address these issues will continue to grow. To demonstrate improvement over time and to meet the upcoming air quality targets, it is essential that emissions performance of mitigation options is well understood and that test data is representative of real-world operation. In addition, thorough assessment of mitigation options is vital to avoid potential reputational damage if technologies are deployed at significant cost to the rail industry with no demonstrable air quality benefit. The aim of the T1235 project is to therefore provide guidance and a protocol for objectively assessing and comparing each realistic mitigation option for its real-world benefits and limitations.

1.2 Project work packages

The T1235 project has been split into four work packages (WPs) as follows:

- WP1 – Identifying **existing approval processes** for retrofit emissions control systems and **available mitigation options**
- WP2 – **Establishing the testing conditions** to assess the emissions benefits of mitigation options and **developing the test protocol**
- WP3 – Identifying the **performance requirements** for retrofit emissions mitigation options
- WP4 – A **literature review of 'off-engine' mitigation measures** such as filtration devices, screens and green walls.

This report provides the results and findings for WP1 and WP4. A latter methodology report and protocol document will provide the outcomes for WP2 and WP3.

1.2.1 Work Package 1: Existing approval processes and mitigation options

The aim of WP1 is to provide a literature review of existing schemes in the road, marine, construction, NRMM and any other relevant sectors for the independent approval of retrofit emissions control systems. The focus will be on any existing or past UK-based schemes, but other relevant non-UK schemes where lessons can be learned, such as schemes ran by the US Environmental Protection Agency (EPA), will be considered. A separate literature review will also be undertaken of the current and emerging retrofit emissions mitigation options for freight and passenger rolling stock, specific to the GB rail sector. Evaluation of the suitability of these options will be based on, but not limited to, packaging within gauge constraints, availability of hardware, operational practicability, and technical feasibility.

1.2.2 Work Package 2: Establishing testing conditions and developing the test protocol

The objective of WP2 is to develop an engine testing protocol which provides a repeatable representation of the common duty cycles for each rolling stock class, with the number of variations of this testing protocol minimised, e.g. by grouping based on common engine types. This will be achieved through data obtained from rail industry organisations that characterises the operating conditions that the various mitigation options may encounter on typical rolling stock classes and the journey types. For each of the retrofit mitigation options identified in WP1, how the emissions performance will be assessed using the engine test protocol will be outlined, including the necessary system preconditioning, number of repeat tests, and weighting of mode points.

How the developed protocol provides cost effective, practical and straight forward methods to benchmark the performance of retrofit mitigation options across relevant rolling stock types will be outlined. The testing protocol will recommend what facility and/or equipment accreditation or certification is required and which existing engine testing standards can be adopted in full or partial form, such as ISO (International Organisation for Standardisation) 8178. All parameters which need to be specified in order to run the protocol, such as ambient temperature and pressure or fuel specification, will be outlined.

Through-life testing may be able to identify engines where emissions increase significantly with age and mileage, as well as help to identify a suitable overhaul intervention period for the engine and/or emissions mitigation. Therefore, the developed protocol will be, where applicable, easily adapted to undertake through-life testing of rail diesel engines and relate emissions measurements back to the original certification levels, either as an ‘as new’ or as an ‘as reconditioned’ state. Any differences that will be required to the testing protocol in order to carry out this through-life testing will be highlighted, with the most appropriate testing frequency, sampling methodology, and the tolerable emissions limits appropriate for such tests stated.

1.2.3 Work Package 3: Identifying performance requirements for retrofit emissions mitigation options

In order to identify the performance requirements for each retrofit emissions mitigation option, appropriate emissions reductions targets for nitrogen oxides (NOx), nitrogen dioxide (NO_2), and particulate matter with a diameter that is 10 micrometres or smaller and 2.5 micrometres or smaller (PM_{10} and $PM_{2.5}$, respectively) will first be identified. The aim of these targets is to be challenging to industry but not overly restrictive, taking into account current technology capability and any potential improvements that are expected. These emissions reduction targets may take the form of either an absolute threshold or a percentage reduction. They may apply on an overall drive cycle basis, be specific to individual mode points such as idle, or be separate targets appropriate to each. All targets should also aim to avoid any significant increases in carbon dioxide (CO_2) or other greenhouse gases, or other regulated emissions such as carbon monoxide (CO) or hydrocarbons (HC).

A suitable reporting format will be outlined for the test data to allow consistency across different duty cycles. This will include information on what component data or specifications for the retrofit emissions mitigation system should be recorded to ensure that the emissions performance can be associated specifically with the emissions-critical components that were tested, such as a catalyst's size or urea grade. Clear criteria will be provided to determine the component changes that will require a new test to be performed and the rationale used to determine how far the emissions performance as tested on the protocol can be applied to other similarly sized engines or drive cycles without requiring a separate certification. Any additional requirements to ensure ongoing emissions performance, such as maintenance and system status messaging, will be determined, including recommending which should be covered by rail industry standards.

1.2.4 Work Package 4: Review of 'off-engine' mitigation measures

A literature review is to be conducted of the likely cost and effectiveness of 'off-engine' emissions mitigation measures such as filtration devices and screens. The focus will primarily be on any previously conducted studies where ambient pollutant concentrations were measured before and after installation of the device, ideally with such studies being carried out by an independent third party. Where such studies do not exist, input from industry stakeholders and expert knowledge has been utilised. A review of each off-engine mitigation device or measure will then be provided according to a set of criteria, specific to use in an enclosed rail environment such as an enclosed station.

The review will cover both commercially available technologies and those which are still in the research phase. Although this work package and the other three work packages are all covering rail emissions mitigation options and schemes, all technologies studied in this work package will be considered separately to the test protocol developed in WP1-3 which is addressed at 'on-engine' or 'on-traction' measures.

1.3 Report structure

Approaches to reducing and mitigating rail emissions can be considered in six categories:

There are six stages to dealing with emissions:

- Engine does not run – no emissions are produced
- In-engine measures – e.g. timing changes, exhaust gas recirculation (EGR)
- Exhaust after-treatment – e.g. selective catalytic reduction (SCR), diesel particulate filter (DPF), Diesel Oxidation Catalyst (DOC)
- Keeping exhaust fumes away from people
- Improved ventilation
- Off-engine mitigation measures

The first three stages are the main focus of this project and are addressed in Work Packages 1 to 3. Section 2 provides a survey and assessment of all relevant 'on-engine' or 'on-traction' mitigation options (i.e. the first three stages listed above) for which an effective testing protocol will need to be developed. Section 3 contains a review of key useful learnings from current relevant emissions retrofit approval schemes for both rail and other sectors. Section 2 and Section 3 thus provide an important foundation for the development of the testing protocol, which will be carried out next during Work Packages 2 and 3.

Off-engine measures, the latter three stages listed above and the subject of Work Package 4, are reviewed and assessed in Section 4.

2 On-engine mitigation measures

2.1 Background and Purpose

The Air Quality Strategic Framework recommended that a "hierarchy of mitigation options" be developed. However, developing such a hierarchy would be heavily reliant upon data from industry on mitigation options and performance, some of which is covered by intellectual property rights and/or is retained for commercial advantage. Some data has been obtained from Innovate UK projects, but in general data, where available, is unlikely to be consistent or comparable.

A realistic understanding of the current emissions picture, plus the effects of any proposed mitigation solutions, and being able to share and examine data for different solutions requires the development of an emissions mitigation testing protocol. The protocol will need to address the full range of realistic mitigation measures on a comparable basis and this section is concerned with compiling and reviewing a list of mitigation measures for which the protocol will be developed.

The list of mitigation measures presented here was originally developed for the RSSB T1233 Air Quality Targets project and has been extended to the address the enlarged scope of this project. It was compiled from expert knowledge and limited available reference material and has been tested and reviewed by multiple industry stakeholders during the course of the T1233 and T1235 projects. This list of mitigation options encompasses measures currently being considered by the ongoing RSSB T1236 Rail Emissions Mitigation – Incentivisation Feasibility Study.

The focus has been on measures that provide real world reductions that would be applicable to GB rail. Thought has also been given to the conditions under which emission reductions can be achieved, for example measures which provide emissions reductions when an engine is in stationary idle in stations have been of particular interest.

Potential measures to reduce emissions often have different emission reduction performance under different circumstances hence an understanding is needed (thus leading to a potential choice) of where emission reduction is targeted. For example, the aim of a project may be to reduce emissions:

i) in stations (and other fixed locations)
ii) onboard (mostly while the train is moving)
iii) or both in stations and onboard.

Another key point of understanding is what level of emission reduction is aimed for on particular rolling stock as part of wider aims to reduce emission from rail sources. The required amount and location of emissions reductions will dictate whether particular solutions can be effective. Thus it is important to understand the origin and detail of the emissions that are aimed to be reduced as some measures are only effective against sub-categories of each broad category of emissions. For example, a Diesel Oxidation

Catalyst unit is only effective at reducing emissions of hydrocarbon-based PM. It will not reduce emissions of PM with very high carbon content carbon PM (i.e 'soot' or 'black carbon') or with mineral content a.k.a. "ash" (both are categorised as 'inorganic PM').

On-rolling stock measures reduce the emissions through one or more of these three routes:

i) Reducing the intensity of emissions under certain conditions,
ii) Shutting the engine off more,
iii) Improving the overall efficiency of the engine and transmission

Hence measuring and quantifying emissions changes via these three routes in a way that aligns to real world use, both before and after changes are made, needs to be able to take in to account if there are:

Changes to mode test points (i.e. a specific engine speed and applied load)?

and/or

Changes to weightings of the mode test points weightings (i.e. the drive cycle)?

The latter two routes to reduce emissions (and particularly often the first) will always require changes in either mode test points or weightings. Cases where there are differences in test points or weightings after installation of a measure have been highlighted in the two right columns in Table 1 below and occur with the majority of measures. This highlights a key requirement of the test protocol to be able to take account of real-world engine use to measure emission performance both before and after potential changes, and thus to provide a reasonable representative understanding of the overall effects of the retrofit solution.

2.2 Introduction to mitigation solutions table

The measures listed in Table 1 have been grouped into the following categories:

a) On engine

b) Exhaust abatement

c) Transmission / auxiliary load handling changes / off-engine rolling stock changes

d) Engine (and potentially transmission) replacement

e) Alternative fuels.

Table 1 List of mitigation measures and impact on mode test points and/or test point weightings post installation of the measure.

Category of measure	**Measure**	Changes required to mode test points post installation?	Changes to mode test points weightings (drive cycle) post installation?
On engine	Best available crankcase breather filtration	No	No
	Exhaust gas recirculation (EGR)	**Slight**	No
	Timing retardation	No	No
	High pressure fuel injection (inc. common rail)	**(Yes)**	**(Yes)**
	Engine remap (where suitable level of computer control and electric transmission)	**Yes**	**Yes**
	Selective cylinder operation (at idle)	No	No
	Improved turbocharger, either two stage or variable geometry	**Yes**	**Yes**
	Charge air cooling	No	No
	Selective engine shutdown (DMU)	**Yes**	**Yes**
Exhaust abatement	Selective catalytic reduction (SCR)	No	No
	Diesel Oxidation Catalyst (DOC)	No	No
	Diesel particulate filter (DPF)	No	No
Transmission /auxiliary load handling changes / off-engine rolling stock changes	Alter transmission gearing ratio so better for route/stopping pattern	**Yes**	**Yes**
	New traction electrical equipment	**Yes**	**Yes**

Category of measure	Measure	Changes required to mode test points post installation?	Changes to mode test points weightings (drive cycle) post installation?
	Electric-powered compressors and battery upgrades	Yes	Yes
	Upgrades for high functionality shore supplies	No	Yes
Engine (and potentially transmission) replacement	New engine (compliant with current regulations)	Yes	Yes
	DMU battery hybrid - mechanical transmission (from DHMU originally)	Yes	Yes
	DMU battery hybrid - electrical transmission (from DHMU originally)	Yes	Yes
	DMU battery hybrid - retrofit for existing DEMU	Yes	Yes
Alternative fuels	Alternative fuel – HVO	No	No
	Alternative fuel – LNG /CNG	Yes	No
	Alternative fuel – Hydrogen IC	Yes	No
	Alternative fuel – Fischer-Topsch	No	No
	Alternative fuel – Emulsified diesel	No	No

A more detailed table is provided in a spreadsheet associated with this report which provides a range of attributes for each mitigation measure. These include

- Each measure's high-level impact on NOx, PM and CO_2 emissions and on fuel consumption, and an indicative cost of the measures per DMU car or locomotive.
- Whether each measure is typically installed in a new engine (for either a DMU or locomotive) that is compliant with the latest emission standards is indicated.

This information highlights that such measures are viable and are already proven in use, as well as highlighting that compliance with the latest emission standards requires integration of multiple measures. It is important to note that implementing a complete new engine solution may involve substantially lower research and development effort and risk overall.

- Whether non-engine abatement measures, such as functional shore supply and electric-powered compressors, and selective engine shutdown on DMUs or variable speed, three-phase traction motors on locomotives, that tend to be installed as part of packages on new rolling stock is indicated. Similarly to on-engine measures, this information highlights where the latest non-engine technologies are viable and are in proven use.
- When certain retrofit measures are installed it is possible that the drive cycle will change, for example, measures that result in greater engine shutdown will have less engine idle running. Similarly, other measures will require changes to mode test points to encompass the new operating conditions post installation of the new measure, for example, installation of new engine. Whether changes to the required test points and to the mode test points weightings (drive cycle) can be expected post installation of a particular mitigation solutions is indicated.
- Suitability of each mitigation solution is considered for each of the following rolling stock classes:
    - Class 153
    - Class 158, 159
    - Class 165, 166
    - Class 168, 170, 171
    - Class 172
    - Class 175
    - Class 180
    - Class 185
    - Class 220, 221, 222
    - Class 66
    - Class 68
    - Class 70

  Suitability covered what circumstances NOx or PM reduction can be expected, i.e. over the typical full drive cycle as well disaggregation by considering impact on emissions in stations (i.e. times of prolonged idling) and on onboard exposure (i.e. potentially prolonged journey times). These two aspects represent the current key rail public air quality challenges. Constraints or potential difficulties in terms of gauging (physical space), availability of hardware, operational practicability and overall technical feasibility were also evaluated for each solution for each rolling stock class.

3 Retrofit approval schemes

3.1 Background

Retrofit schemes have typically not been applied to on-road engines, which have comparatively short working lives when compared to rail engines. For example, the average car lifespan in the UK is just under 16 years, while HGV tractor units experience intensive use in larger fleets for only seven years. If an engine's working life is short, then there is little need for retrofit schemes as the engine will be replaced regularly with a model meeting a newer stricter standard as there is a reasonably large annual turnover of engines.

In addition, other measures deployed in areas with high emissions to improve air quality, such as the Ultra Low Emissions Zone in London, can force the earlier uptake of newer vehicles. Furthermore, due to road transport's large contribution to national air pollution, more stringent regulation of road engine emissions has tended to be introduced earlier than for non-road engines. All of these factors mean there is a limited need for retrofit schemes to address emissions reductions for the road sector.

Retrofit schemes have therefore mainly focused not on road engines but on non-road engines with long in-service lives; this includes rail, but also covers marine, stationary generators and some construction equipment. Reviewing current retrofit schemes from both rail in other countries and other non-road sectors allows for any lessons learned from these schemes to be applied to a retrofit approval scheme for GB rail, enabling efficient and effective deployment of such a scheme.

3.2 Evolutionary history and lineage of retrofit schemes

Retrofit schemes tend to fall into certain "ecosytems" whereby later schemes reuse aspects of earlier schemes. There are three main ecosystems of engine retrofit schemes that apply to non-road transport:

- **United Nations Economic Commission for Europe (UNECE)** developed an engine retrofit approval scheme, R132, for older NRMM engines in Europe
- The **US Environmental Protection Agency (EPA)** administers non-road engine retrofit schemes across a variety of sectors
- The **International Convention for the Prevention of Pollution from Ships (MARPOL)** instigated a retrofit scheme for the international marine sector.

These schemes are often fairly limited in scope, but have been used as a basis and adapted for other later schemes which draw upon their successes and respond to their limitations. For instance, the UNECE R132 non-road approval scheme was used as a basis for the Commercial Vehicle Retrofit Approval Scheme (CVRAS) developed by the Low Carbon Vehicle Partnership (now called the ZEMO Partnership) and run by the Energy Saving Trust, which is targeted at longer-life on-road vehicles used in urban areas, i.e. buses and refuse lorries. This scheme then, in turn, became the basis for the construction equipment scheme as administered by the Energy Saving Trust on behalf of the Greater London Authority. However, as these schemes cover non-rail NRMM, their applicability to rail is limited but there are useful learnings regarding overall philosophy and scheme administration.

The US EPA runs a variety of individually tailored retrofit emission schemes that cover rail, but which also cover other individual non-road sectors such as inshore/inland marine, stationary generators and pumps, underground mining equipment, and heavy equipment (e.g. construction equipment). These are sector-specific retrofit or upgrade requirement schemes that are aligned to relevant new engine certification for that particular non-road engine use, whereas the other non-US retrofit schemes mentioned above tend to be a lot broader in scope and application.

MARPOL is of relatively limited relevance to rail since its main focus is on shipping related problems such as SO_2, NOx and VOC and there is more emphasis on regional or global impacts of larger quantities of pollutants. The MARPOL regulations for the Prevention of Air Pollution from Ships (Annex VI) focus on reductions in air quality pollutants emissions at both regional and local levels with stricter requirements in defined regional Emission Control Areas (ECAs). The ECAs combine regions with air quality issues and governments pressing for action to reduce marine emissions. Annex VI aims to improve air quality in more polluted areas through:

i) The use of cleaner burning fuels in all engines, targeting substantial reduction in SOx, along with VOCs and PM. Even lower fuel sulphur levels are required in ECAs
ii) The introduction of less polluting engines primarily targeting reductions in NOx emissions progressively over time in three stages: Tier I (2000+), Tier II (2010+) and, for ECAs only, Tier III (2016+ engines from 2016 or 2020 depending on the ECA)
iii) The reduction in NOx emissions of engines produced between 1990-1999 to meet Tier I (2000-2009) levels if the OEM has approved a suitable retrofit kit for the engine that has minimal performance impact. The kits are designed to reduce the initial production of NOx by changes to fuel injection and timing with no intention for the retrofit of exhaust abatement technologies, emission testing for retrofit aligns with new engine testing for Tier II and III.

Most land-based emission sources have previously transitioned to cleaner burning fuels and virtually eliminated some of the issues that offshore marine still faces. Very large slow speed 2-stroke marine engines in larger ships typically produce higher NOx emissions than smaller faster rotating engines used in rail or smaller vessels due to the comparatively long time period that the in-cylinder temperature remains above the NOx formation temperature during and after combustion. This leads to intrinsically higher rates of NOx formation that are initially optimally tackled with on-engine changes to combustion parameters (Tier 1 and II) and with additional on-engine and abatement measures only for Tier III.

Because of the limited transferability to rail, this scheme will not be discussed further in this report.

3.3 Description of Schemes

This section provides descriptions and relevant learnings for rail for the following emissions retrofit schemes:

- United Nations Economic Commission for Europe (UNECE) R132
- Clean Vehicle Retrofit Accreditation Scheme (CVRAS)
- Greater London Authority (GLA) construction equipment
- US Environment Protection Agency (EPA) Rail
- US EPA National Emission Standards for Hazardous Air Pollutants (NESHAP) – Reciprocating Internal Combustion Engines (RICE)
- US EPA Marine
- US state/local schemes

3.3.1 UNECE R132

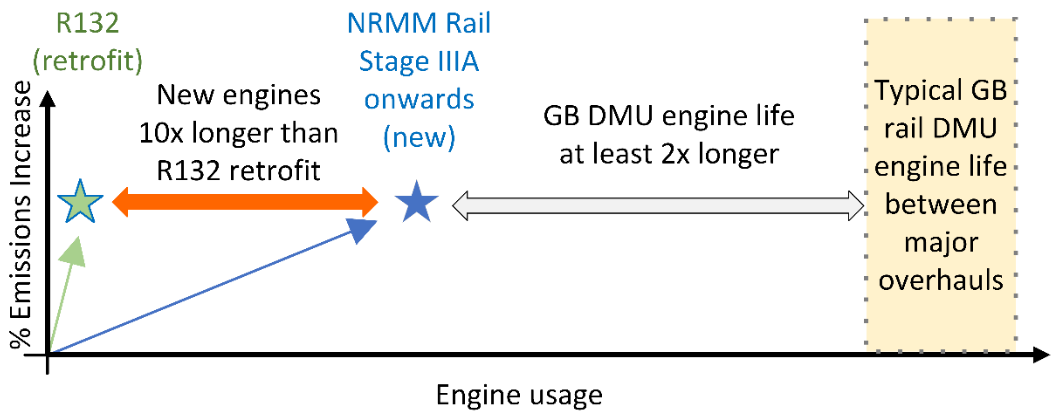
The UNECE certification scheme entitled Regulation No. 132 or R132 (UNECE, 2015) is aimed at enabling certification of "retrofit emission control solutions" for older NRMM engines. The scheme is just relevant to the certification of engines, and does not address administrative aspects. Thus it is not a template for rolling out a complete retrofit approval scheme but it does provide a core building block. R132 serves, then, as an example of how a certification scheme with certain key elements can be adapted for use in a complete scheme.

Using specified technological solutions that were developed for the Euro V/VI emission standards for road, the scheme aims to reduce emissions of PM or NOx or both from medium-sized diesel NRMM engines using "off the shelf" solutions. Essentially, the only solutions covered by this scheme are Diesel Oxidation Catalyst (DOC), diesel particulate filters (DPFs), and selective catalytic reduction (SCR). As a result, for NOx and PM the minimum reductions post retrofit (compared to engines "as is" state) are 60% and 90%, respectively. An important aspect of the scheme is its simplicity in specifying relative required improvements. However, it does not address hybrid solutions or stop-start technologies.

The scheme aims to utilise a limited number of Heavy Duty (HD) road-based mitigation solutions, such as DOC, DPF and SCR, with minimal extra development to thus reduce costs and lead to a quick turnaround. Consequently, the scheme is therefore limited to mid-size NRMM engines where HD solutions are readily transferrable, rather than locomotive or larger diesel multiple unit (DMU) engines where solutions are not readily available.

The testing requirements are similar to those applied to new engines through the UNECE R49 (ISO 8178) scheme, but some requirements have been loosened to allow for retrofitting to take place. For example, the emissions performance of engines and abatement systems deteriorates with increasing usage and emissions certification processes aim to take account of some of this deterioration. For R132 the emissions "durability" requirement is tested at 1/10th of the new engine durability time period for the new rail engines (which substantially reduces testing costs, however the permitted degradation (deterioration) in emissions is the same as for new engines. Thus the requirement is effectively much less strict than for new engines because the time interval over which degradation is assessed is 1/10th of that for a new engines. In terms of durability, the durability period for retrofit engines becomes 1000 hours (i.e. 41 .7 days of running), instead of 10,000 hours for new rail engines. New rail engines also have longer emission durability period than other NRMM sectors which are typically 5,000 or 8,000 hours.

Figure 1 Illustration of permitted increases in engine "emissions durability period" with engine usage for R132 retrofitted NRMM engines and new European NRMM Stage IIIA onwards rail regulatory certification requirements in comparison of typical DMU engine life between major overhauls.



All testing has to be performed based on the ISO 8178-C1 drive cycle, which assumes 15% of time in idle. (An abbreviated version of ISO 8178 and other associated engine testing material is incorporated into UNECE regulations as R96.)

Despite covering many of the same on-engine mitigation options available to rail, the UNECE R132 scheme has only limited usefulness for rail. This is because it covers only a limited range of technology solutions and it only covers a single drive cycle. In addition, the idle requirements in this scheme are significantly different to the real-world lengths of time spent in idle for rail, where a train typically spends around 60-70% of its time idling on average due to substantial time idling in stations and depots as well as coasting while in motion.

However, one of the strengths of the scheme, which can be applied to rail, are the clear requirements that specify the component and hardware specification data (such as the individual catalyst types used) to be collected on DOC, DPF and SCR solutions to ensure the products installed match those submitted for certification.

3.3.2 CVRAS

Developed by the Low Carbon Vehicle Partnership (LowCVP), now named the Zero Emissions Mobility (ZEMO) Partnership and run by the Energy Savings Trust (EST), the Clean Vehicle Retrofit Accreditation Scheme (CVRAS) covers commercial vehicles used in urban areas (Zemo Partnership, 2021). The scheme was developed as a response to previous UK governments having identified the need for a retrofit scheme for commercial vehicles with longer lifespans, particularly buses and refuse collection vehicles. This scheme has and is being used as prerequisite for grant-funding programmes, for example, for bus retrofits.

Based upon this, four potential retrofit pathways were identified. The first is exhaust abatement systems which has had the greatest take up. The second most popular retrofit pathway involved new engines that were compliant with the latest regulations, with manufacturers suggesting that engine and engine control unit (ECU) changes would be needed to deliver large reductions in addition to abatement options. A third pathway was identified that focused on liquified petroleum gas (LPG) conversions for taxis which saw limited initial take up and limited sustained interest. Finally, the scheme also explored battery retrofitting including hybrid solutions, although this pathway saw the least deployment across the sectors, with battery hybrid solutions on buses never being deployed in high volumes.

Since CVRAS was based upon the UNECE R132 scheme, it took the targets of percentage reductions from original engine emissions (60% for NOx, 90% for PM) used in the R132 scheme and attempted to convert them into additional g/km targets for specific use cases. In a slight adaptation from UNECE R132, the targets were measured against the original standards the engine complied with when new rather than against measured pre-conversion emissions and no specific standard compliance. A factor that contributed to the discrepancy between real world and testing performance (of both new and retrofitted engines) were the drive cycles chosen. These drive cycles were then used to convert percentage reductions targets to g/km targets. However the drive cycles chosen did not accurately reflect the real urban usage (with higher g/km emissions). For example, real world on-road idle was assumed to be 15% of the duty cycle which is not representative of real-world usage in large urban areas.

This scheme does highlight the importance for real-world testing before retrofit solutions are installed across a fleet. Emission reductions from retrofit solutions have been significantly smaller in practice than had been anticipated. Policymakers backed CVRAS as they believed that abatement solutions would quickly and more economically deliver Euro V/VI standards. 600 buses were retrofitted by Transport Scotland at a cost of £10 million in order to reduce NO_2 emissions from older Euro IV and V diesel engines and to attempt to achieve compliance with Euro VI emission standards being mandated as part of the low emission zones (LEZs) that will be enforced in Glasgow, Edinburgh, Dundee, and Aberdeen being introduced over the coming years. Transport Scotland were aware of earlier issue with CVRAS and required some enhancements to meet their LEZ goals: Euro VI compliance, minimum 80% reduction in NOx and 99% reduction in PM. However, in service testing conducted by Transport Scotland (2021) later revealed that the retrofitted buses did not comply with the applicable euro VI NOx standards as the real-world performance of the retrofitted engines varied considerably from the pre-installation testing results suggested due to the differences in drive cycles. Additionally, in some cases the retrofitted equipment was not optimally installed or the software algorithms were not controlling Ad-Blue dosing correctly in real-world use. This example clearly shows the importance of making testing protocols and other technical requirements for retrofits to be as robust as possible. PM reduction, however, was measured as being better than mandated in real-world use.

Another important aspect is that installation of some Euro VI technologies does not necessarily lead to compliance with Euro VI because other changes, including installation of higher efficiency crankcase breathers, timing changes, ECU adjustments, engine cooling changes, higher pressure fuel injection, and often fitting EGR, are not made at the same time. To achieve Euro V/VI compliance and emission reduction nearer expected levels, additional on-engine improvements are also needed as part of a harmonized package.

At the time of writing, there are signs that the long life-span commercial vehicle sector is moving away from retrofits, especially simple exhaust abatement. Evidence of this can be seen in the Transport for London bus fleets. Some older diesel buses did receive exhaust retrofits, but activity in recent years has focused on replacing older engines in existing buses with Euro VI engines or the buses replaced either with new hybrid buses with Euro VI engines, as well as new battery only buses now joining the fleet, resulting in significant emission reductions. With such technologies now becoming widely available, it is highly likely that 'peak retrofit' regarding road vehicles has already passed.

3.3.3 GLA construction equipment

The Greater London Authority (GLA) has a two-part scheme to drive emission reductions from construction equipment by encouraging and supporting both retrofit options and new models[1]. This GLA scheme is based upon UNECE R132 and CVRAS and is administered by the EST on behalf of the GLA. The scheme includes geographical zones

[1] https://www.london.gov.uk/what-we-do/environment/pollution-and-air-quality/nrmm

with stricter requirements in a Central Activity Zone (closely aligning with Transport for London Zone 1) and Opportunity Areas for redevelopment. To support improving air quality, the minimum requirements for the scheme get tougher over time with the intention of enabling zero tailpipe emissions in 2035. Required compliance with non-road mobile machinery (NRMM) emission standards Stage IIIB, IV or V standard limits depends on each individual engine application and in some cases geographical location of usage, with the minimum standard required in each case being stepped up over time with complete Stage V compliance required by 2025. Table 2, which is from Cleaner Construction for London (2020), shows the different requirements by geographic zone and engine type. The emissions reductions in practice vary between applications and the scheme covering a wider range of end applications than the R132 and CVRAS schemes.

Table 2 GLA construction equipment requirements from 1st September 2020

Engine type	Geographic Zone	
	Greater London	Central Activity Zone / Opportunity Areas
Variable speed	IIIB	IV*
Constant speed	V**	V**

* Stage IV machinery is not widely available between 37 - 56 kW. However, Stage V machines are available, and as Stage IV is the minimum standard, machinery at these sizes will often need to meet Stage V.
** Stage IIIB and IV emission limits are not defined in legislation for constant speed engines, therefore the emission standard required for those engines is effectively Stage V.

The GLA scheme has been very successful at driving real-world emission reductions from stationary generators, mostly due to the ISO 8178 D1/D2 test drive cycle and the in-service drive cycle being closely aligned. For stationary generators, from the beginning of the scheme, the Euro 5 standard was required to be met. In contrast, some equipment types, such as excavators, have very different drive cycles to the regulatory test drive cycle which is ISO 8178 C1 for this type of equipment. This same issue of disparity between test drive cycle and real-world drive cycle is likely to occur in rail engine use as well. As a result, PM reduction has been realised for excavator retrofits but little improvement has been seen for other pollutant emissions. At the start of the scheme, a lack of understanding of the real drive cycles and their variability for many types of construction equipment contributed to this discrepancy. Understanding of the real-world excavator drive cycles has improved as a consequence of the scheme being implemented, but data collection remains a challenge. The issue of unrealistic and inaccurate baselining crops up in many retrofit schemes, not just the GLA construction equipment scheme.

The scheme has highlighted that retrofitting involving SCR is not as effective at NOx reduction in practice as was expected. In contrast, PM reductions line up more closely with initial expectations. The scheme has also highlighted that for some applications there have been issues with finding space to retrofit equipment; similar issues can be expected in the rail sector.

Due to the nature of construction equipment operating in fixed locations for extended periods of time, overall emissions reduction occurs at fixed locations and the scheme is therefore an effective measure at reducing emissions in urban areas and thus improving urban air quality. In contrast, rail emissions vary by location and therefore public exposure to rail emissions is more variable.

Some exemptions are included in the GLA scheme. Flooding or other emergency response equipment is exempt, as is certain equipment (such as certain pile drivers) which are not possible to retrofit: the focus of the scheme is not necessarily 100% compliance but rather on achieving effective large-scale reductions.

If the time scale to modify and test an engine is very long, then an application for deferred compliance can be made. Also there is a realistic appreciation of variable manufacturer support for older products. It is important to note that the lack of OEM support could be an issue for older DMU engines in GB rail.

Overall, air pollution reduction has been achieved by the vast majority of applicable equipment, even if it has not been seen for all types of equipment involved in the scheme.

3.3.4 Introduction to US retrofit approval schemes

In the US, NRMM retrofit schemes are tailored to each sub-sector use since a "one size fits all" NRMM retrofit solution is not recognised. Furthermore, retrofit approval schemes in the US are set out in the relevant new engine regulatory and certification requirements for each subsector, which will vary according to engine age. For example, backup generators are treated differently from other types of generators. The location of equipment is also taken into account, such as mining trucks which are used in very remote locations and therefore do not significantly contribute to public emissions exposure.

3.3.5 US EPA Rail

The US rail engine regulatory emission standards were the first in the non-road sector in the US, with engine certification and standards controlled by the Federal Government, via the US EPA.

An extensive research and development programme in the 1990s involving modelling formed the backbone for this scheme which was introduced for new engines in 1999. This programme was informed by work carried out in collaboration with the rail industry from 1968 onwards on a long-term voluntary basis. Some recommended voluntary changes to both engines and locomotives were introduced by 1973. These included improving fuel consumption and improving combustion to reduce VOC emissions in order to address air quality issues. The need for a notch-based understanding of emissions emerged at this time. Regulations that came into force from 1999 required one compulsory upgrade or retrofit during an engine's working life. This covered both new engines manufactured from 1999 onward as well as older engines manufactured after 1973.

Each US Tier standard for new engines has an associated "plus" standard that upgrades or retrofits of existing engines have to meet by a certain date. For instance, for engines manufactured during the voluntary period for addressing emissions between 1973 and 1999, their classification is Tier 0 and, if these engines have upgrades once they reach the regulatory working life limits, they are required to meet the Tier 0+ emission standard. In many parts of the US, including California (which has reached voluntary agreements with the major operators), engine upgrades have become so extensive that some older engines that were initially Tier 0 are now compliant with Tier 2+ standards.

Unique to the US EPA rail emissions regulation compared to other sectors and other countries is the far greater focus on the emission reduction throughout the entire lifespan of a locomotive, rather than the performance of its engine at the point of leaving the factory.

The frame of reference **is therefore *the total real-world emissions over the entire life of the locomotive.* To achieve this there are multiple potential pathways*, of which retrofitting is only one option*:**

- Minimising the increase in emissions from the engine due to use during its lifetime (emissions durability)
- Restoring overhauled engines to original emissions performance (i.e. revert to as manufactured condition)
- Retrofitting overhauled engines to an improved emissions performance compared to its as manufactured condition
- Installation of new engines that meet a more recent emission standard (currently Tier 3 or Tier 4)

A major element of the US EPA rail emissions regulations is ensuring high engine durability of emissions performance and minimising degradation whereby the emissions would increase due to engine use. While rail has the strictest durability metrics in both US and Europe when compared to other HD road or NRMM emission standards, it is important to note that the US emissions durability requirements for all sectors are higher than any equivalent in Europe and those for rail are significantly higher. All technologies considered when looking at meeting emissions targets in the US have to have proven effectiveness, durability and cost effectiveness. High durability technologies include:

- Crankcase breather improvements
- Fuel injection improvements
- Timing changes

- DOC
- EGR
- Improved handling of loads through, for example:
  - Use of a single electrical rotating machine that supplies all electrical requirements and can perform the role of the start motor, which could thus replace the main (traction) alternator, auxiliary alternator, generator and starter motor
  - Increased efficiency and controllability of compressors or cooling systems by moving from mechanically powered to electrically powered systems with sophisticated control mechanisms.

Technologies with lower durability have been found to be:

- DPF which is susceptible to clogging over time as regeneration is never completely effective
- SCR in terms of degradation and thus reduced effectiveness over time.

As part of the through-life testing requirements 1 in 125 or 1 in 250 engines are tested to ensure real world emissions matched those during initial testing. This testing is only mandatory for larger fleets, with through-life testing starting at 50% of the "working life" (defined by US EPA as a nominal time or total energy usage limit) of the selected engines. If engines do not pass the through-life testing that occurs at 50% of the working life, then they are required to undergo an engine overhaul to restore the original emissions performance, or a once-in-life retrofit. Overhauled engines are then restored to the relevant an "as retrofitted" condition. This requirement is based on through-life testing research, and so the engine usage limit will either be a certain time or MWh limit, whichever comes first. For example, the default is 7.5 years for locomotive engines and the MWh limits are based on the engine power and drive cycle, based certification testing data. Good emissions durability performance for a complete engine package is rewarded under the scheme whereby longer intervals between testing are permitted, with highly durable engines able to go intervals of 11.5 years (or the MWh equivalent) between regulatorily required overhauls, better aligning with the heavy maintenance cycle.

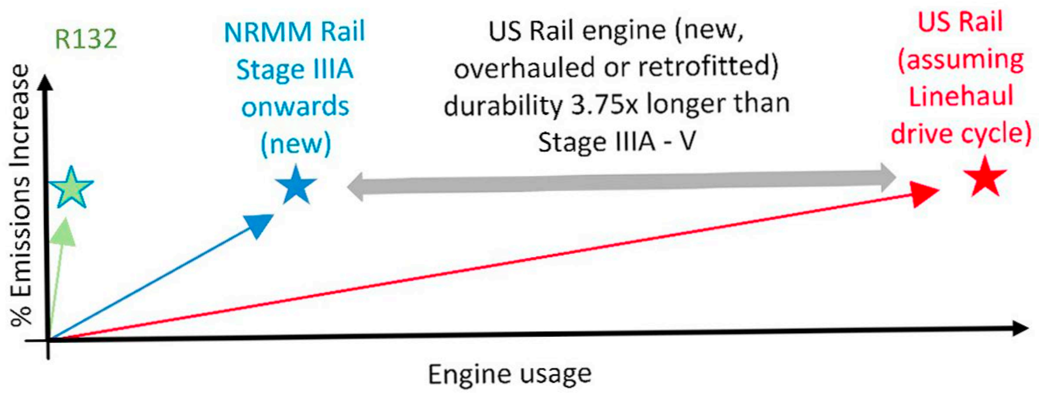
Since rail emissions regulation has been running for so long in the US, repeated modelling using testing data has shown that the focus on durability of emissions is very effective at reducing total emissions.

Measuring durability focuses on two metrics:

- The percentage increase in emissions at a specified usage level
- The engine usage level specified (varies by engine end use).

On both these fronts, the US metrics are stricter than Europe. It is therefore evident that *durability has a large, mostly hidden impact on real world emissions* as demonstrated in Figure 1.

Figure 2 Illustration of permitted increases in emissions "emissions durability" with engine usage for new rail engines for the US EPA rail and European NRMM rail regulatory certification requirements



In addition, the regulatory drive cycles used for US rail are based upon measuring real world engine usage in three different categories: for main line freight, local/yard freight (which typically idles more than main line freight), and passenger trains. Unlike in Europe, in the US idle is defined for testing purposes to include most real-world auxiliary loads. Regulatory drive cycles can evolve over time, for example the regulatory drive cycles were changed when fitment of stop-start technology reduced the average proportion of time in idle. The rail emission weighting maths in the US is normalised using the time in each notch, whereas in Europe it is effectively normalised based on the power in each notch compared to the total power during the test cycle. Consequently, the US method gives equal importance to each notch based on the time specified in the regulatory drive cycle when it comes to emission weighting, which leads to a much bigger focus on reducing emissions at lower engine power than the European method of weighting. This has led, in the US, to use of EGR which can reduce idle emissions (for example equivalent MTU engine sold in Europe are fitted with EGR for the US market). While reductions between successive tiers of US emissions certification limits appear smaller when compared to the European NRMM scheme (which apply to rail), greater real-world impacts are realised by the US scheme.

A challenge for the US rail scheme, however, is how to certify DMUs. Due to a high fatality crash in 1940 (in Cuyahoga Falls, Ohio), DMUs have not been popular in the US, but in recent years they have come back into favour. Currently DMU engines <30L and <750 KW are treated as marine engines for certification purposes which is a less stringent regulatory regime compared to rail. Up to this point, all guidance in the US has been based on locomotives and it is likely to take extensive research and work to create a similar level of detail for DMUs, including handling retrofits.

In the US, there is a focus on carefully specifying the parts and designs for retrofits (in all sectors but which started from experiences in rail including regulating "like for like" replacement aftermarket parts), so that *what was tested* is *what is supplied.* Most required retrofit upgrades are based on a "certified kit" concept. The testing of the kit is done by kit providers and there are no post fitment testing requirements. To minimise cost and down time, kits are usually fitted during major engine overhauls and some kit components are those that need replacing at engine rebuilds anyway due to general wear. Some very large operators, such as Norfolk Southern, do develop and install their own kits utilising a mix of component suppliers. In terms of certification, some regular overhaul parts that do not provide an improvement in emissions, but which impact emissions are also certified, such as fuel injectors.

Overall, reviewing the US EPA scheme has revealed that durability requirements and the definition of regulatory drive cycles influence choice of technologies for both new engines and retrofit kits. The focus of US rail emission regulation is not just to reduce emissions by setting stricter targets for new engines but on the emissions performance across the entire lifetime of the engine through reduced degradation, restoration of as new factory performance and often an upgrade from as new emission performance aligning with an engine rebuild. Emissions reductions are seen across a range of engine power outputs including at lower engine powers too, where some of the reduction is due to improved overall energy efficiency.

3.3.6 US EPA NESHAP – RICE

The US EPA created the National Emission Standards for Hazardous Air Pollutants (NESHAP) for reciprocating internal combustion engines (RICE) which cover stationary engines[2]. These standards cover generators and pumps, with some of the engines covered used only very infrequently, such as back-up generators. Many of these engines have long lifespans and therefore replacement with newer engines occurs extremely infrequently. A compulsory retrofit requirement was introduced to align with the start of revisions to new engine standards requiring older engines to be retrofitted before the end of 2012.

As part of the preparation for the compulsory retrofit requirement, an extensive research programme was launched to assess the emission reduction and cost effectiveness of potential retrofit options with real world testing. The focus was on options that were low cost, easy to retrofit, and effective at emissions reduction across a range of engines. The aim was therefore to specify technologies where original equipment manufacturers (OEMs) and third parties would be able to supply solutions, with limited concern about reaching some guaranteed percentage reduction for a given engine model.

To achieve reductions in PM emissions, the selected core technologies were improved crank case breathers (i.e. higher filtration effectiveness) and DOC. DPFs were less effective as the incremental emissions reduction after fitting improved crank case breathers and DOC was limited. Furthermore, older engines do not have the capability to enable effective regeneration of the DPF which leads to increased degradation over

[2] https://www.epa.gov/stationary-engines/national-emission-standards-hazardous-air-pollutants-reciprocating-internal-0

time. However, DPF could be used as an optional add-on in an areas with poor air quality where operators were subject to wider emissions compliance requirements. As regards NOx emissions reduction, no technologies were promoted as none were found to meet the criteria stated above, with SCR being difficult to retrofit to stationary engines (due to complex reconfiguration and older engines being retrofitted lacking the computer control and sensors that can aid fitting SCR on newer engines) as well as being costly compared to the PM reducing technologies.

Overall, the aim of the scheme was to produce some relatively easy improvements in air quality by going for the "low hanging fruit" using well understood, robust technologies. The focus was therefore primarily on efficiently effecting reasonably sized and easy reductions under a wide range of conditions, with no focus on specific target percentage reductions or any other metrics. The total emissions from stationary engines in the US do not equate to a large emissions source overall, which is similar in proportion to UK rail in relation to the UK's total emissions. The relatively simple approach meant that no testing was required of end users and helped ensure a high degree of compliance.

3.3.7 US EPA Marine

Based upon the relatively successful US EPA rail scheme discussed in Section 3.3.5, new and retrofit regulations were also introduced for US EPA marine. Based upon real marine use, the marine regulations have different engine test points and different drive cycles. In general, the marine scheme is less stringent than the rail scheme, with lower durability requirements and more relaxed working life definitions. Retrofit requirements started between 2008 and 2013 for different engine types and variants, with a focus on those with high sales volume first.

Retrofitting is required when a major overhaul of an engine is needed, and so key components that are effectively life expired are replaced with improved lower emissions components. As with the US EPA Rail scheme, the US EPA Marine scheme had the same standard "kit" concept as used in rail, whereby the kit providers carry out all testing and there is no end user testing. However, unlike rail there is no through life testing requirement for end users. The aim of the US marine retrofit scheme is for reasonable but not total coverage of all marine engines and so a reasonable number of exemptions are available – just 50 individual engine variants that have been manufactured since 1973 are covered by the retrofit requirements. By far the most common type of vessel ownership is single-vessel ownership, however the scheme is designed to suit all operators, not just large operators which are the focus of the rail retrofit programme.

3.3.8 US State/Local Schemes

In the US, state governments and regulatory agencies do not have the authority to set regulatory standards but they can enforce the use of new or retrofitted equipment that meets newer standards, either state-wide or locally.

The California Air Resources Board (CARB) has banned operators from using older locomotives in the state; however, this usually just means these locomotives continue to be used elsewhere in the US. In addition, maximum idle time limits are expected to be introduced by CARB in 2022, indirectly encouraging increased use of Automatic Engine Stop/Start and shore supplies. CARB's current goal is to achieve "zero emissions" from the rail sector by 2035.

The future aim in California is to only allow one engine overhaul during an engine's working life in California, but this has not yet been converted into a regulatory requirement. A consequence of such a requirement would be that older locomotives would likely be moved to the other 47 mainland states rather than being scrapped. The average age of the freight locomotive fleet in California is already lower than in the rest of the US. Any locomotives bought since 2012-2018 (depending on which engine usage limit applies to the engine) could still be used in California up to the 2035 zero emissions target.

Electric-only rail operation has been enforced since 1908 in either tunnels or terminals for both passenger and freight trains in Manhattan in New York City. The Kaufman Electrification Act 1923, enacted by the New York State Assembly, also banned steam use from all of New York City and the surrounding urban areas which rapidly pushed the switch to electric or diesel operation. This act mandated the electrification of all railroads in New York City by 1926 and, although the act was eventually successfully overturned and deemed unconstitutional (Staten Island Rapid Transit Ry. Co. v. Public Service Com'n, 1926), it still contributed to the high degree of electrification seen today in New York City.

Many state governments also aim to reach voluntary agreements with large rail users. These agreements usually involve agreeing the use of locomotives that meet minimum emissions standards , either from new or upgraded, rather than just the minimum federal mandated upgrade, e.g. from Tier 1 to Tier 1+.

In California the 12 worst rail air quality locations are targeted and require a minimum of either Tier 3 (unless the locomotive is a late vintage Tier 2 build and has been stored out of use for a while) or if it has an older engine it has been upgraded to Tier 2+ (i.e. not the potential lesser federal requirements of upgrading from Tier 0 to 0+ or Tier 1 to 1+ but to Tier 2+). In Georgia the two worst rail air quality locations are targeted, in a similar way to California requiring mostly cleaner locomotives (less strict than the California equivalent). At these locations, specific actions are agreed upon, such as retrofitting yard locomotives at those locations where, for example, a Tier 0+ engine may be retrofitted to achieve a Tier 3+ classification. Sometimes at these locations yard locomotives are required to be battery operated or there is a move towards reducing idle and increasing shore supply use.

Looking at the wider picture in California, it has become clear in the last three years that there is better overall value from electrifying container-handling equipment compared to cleaning up rail emissions. Consequently, the state has quickly mandated zero emissions from new container-handling equipment by 2023. Similar off-rail benefits could be seen for rail in the UK, but it is unclear where the boundary between the best value emission reduction in rail and the equipment and cargo handling equipment may lie, since at larger container facilities in the UK a larger proportion of the handling equipment is already electrically powered compared to California. Some GB aggregate rail terminals already have 100% electrically powered cargo handling equipment e.g. Stewart's Lane in Battersea.

States can also incentivise rail air quality improvements in other ways, such as funding research and development to assess emissions reductions in practice and whether a measure is a reliable product, as well as First of a Kind type schemes. CARB has had a huge impact in this area, as over the last three decades they have funded the first rail DOC, DPF, SCR and genset locomotives trials as well as other initiatives. These trials examined the effectiveness of emission reduction in real-world usage with **long-term usage trials carried out to discover issues before large-scale deployment**. As a result of these longer-term trials, genset locomotives were considered not to be cost effective (fuel savings were less than predicted) or sufficiently reliable and thus were not deployed. In 2015, CARB started offering battery locomotive research and development funding (focussing on local use in California due to the in-state benefit requirement for funding) as part of a wider programme looking at freight terminal emissions reduction. Through this programme, a Wabtec (formerly GE) battery locomotive was developed with the first sale in Australia (in September 2021), albeit with a long-distance specification: two more traction motors and a significantly larger capacity battery pack than the initial development model. The Canadian National (CN) railroad (which has core operations in 10 states in the US) has also recently (November 2021) placed an order with the same specification using some state grant funding from Pennsylvania. In the case of both Wabtec orders the intention of the end users is never to plug in the locomotives to recharge but to use them in conjunction with two diesel locomotives with the energy for battery recharging coming from regenerative braking. Electro-Motive Diesel (EMD) also developed a battery yard locomotive that has been sold in California, though the specification and performance is suited to the local use envisaged by CARB (the EMD locomotive is very similar to the Clayton battery-diesel hybrid locomotives ordered by Beacon for use in yard applications in GB). The other strand of this CARB research programme examined the barriers to full roll out of electric container handling equipment, with research suggesting that electrifying this equipment would be the best value way to reduce emissions in the short term, rather than focusing on locomotive emissions, leading to California's recent rapid push to electrify container handling equipment.

3.3.9 Future road emissions regulation in Europe (Euro 7/VII)

There are many lessons learned from previous road emissions regulations in Europe that are now in the process of being applied to the development of the future Euro 7/VII standards for road vehicles. The main air quality focus up to and including in Euro 6/VI has been on reducing NOx and PM emissions, with some attention on tackling other pollutants such as unburnt HC. In the ongoing discussions about the new Euro VII standards, the focus is now turning to reducing emissions in urban areas in particular, rather than in the countryside. This will require reduction of NOx emissions at low exhaust temperatures where SCR has limited effectiveness.

A shift towards longer assessment periods for emissions durability is also being considered that is on par with engine life and rebuild intervals.. The new regulations will also make an effort to assess nitrogen oxides (NO, N_2O and NO_2) separately, as well as reducing other emissions that are both air quality pollutants and greenhouse gases such as finer PM, CH_4 and N_2O. It is expected there will be a tighter focus on unburnt hydrocarbons. (It is worth noting that methane, volatile organic compounds, polycyclic aromatic hydrocarbons (PAH) and residual HC are less effectively removed by abatement, i.e. DOC.) There is a large push towards increased CO_2 efficiency, especially for an engine to be more efficient in low power and reducing idle fuel use – this efficiency-based approach aligns with US EPA and CARB rail regulatory philosophy.

For Euro 7/VII, idle is likely to be considered differently to previous European road standards. In most real-world conditions, idle is at least a lightly loaded condition, but test procedures usually ignore this fact. A common misconception is that hardly any power is produced at idle, but this is not the case in real-world usage where auxiliary and hotel loads must be met. For example, real idle for a DMU engine might be 25-60 kW and usually involves very low air to fuel ratios – these two conditions together create a perfect environment for high emissions output on a g/kWh basis. British train Classes 185 and 68 can even have idle loads of more than 100 kW and 500 kW per engine, respectively.

3.3.10 Recent Emissions Regulation Changes in the US

Although no new emissions regulations are being proposed (or are even in development), a far bigger emissions reduction impact is expected from changes not related to potential new stricter standards as collectively these changes have been modelled as having a far bigger impact over the next two decades than further tightening of emission standards beyond Tier 4. For example, the replacement of older equipment over time with Tier 4 compliant equipment, has been modelled as having a far bigger impact over the next two decades than further tightening of emission standards beyond Tier 4. There has been limited trials of zero (tail pipe) emission technologies which include battery and soon hydrogen fuel cell solutions starting in

2022 to replace older diesel locomotives. Other potential options being examined include retrofits requirements that go beyond the minimum required “Tier+” upgrades (as California has been doing with voluntary agreements),. For any future standard post Tier 4, there is limited room for further large emissions reductions, and for which viable technologies are available. A key learning for GB rail is the substantial cumulative emissions reduction benefit from moving as soon as possible to retrofit existing engines where practical rather than making limited improvements to newer rolling stock that already have comparatively low emissions.

In 2021, some additional requirements to emissions regulation took effect in the US which included methane and nitrous oxide being added to the list of gases required to be measured during rail engine testing. However, these gases are not regulated – this testing is currently only occurring as an information gathering exercise (a standard step in the development of US emission regulations). This testing will apply to both current Tier 4 engines designs and to examples of older Tier 0 to Tier 3 engines that will be measured as part of in-life emission upgrade requirements and an engine emission durability review (a processes that was defined in the early to mid-1990s). This approach allows data to be quickly gathered on all in-use engine variants. In addition, more data on engine maps is planned to be recorded, with learnings taken from Tier 4 that required significant reductions to idle emissions and changes to engine rpm and fuel injection parameters..

3.4 Key learnings and recommendations

While there is no single ideal scheme that will directly and effectively translate to GB rail, there are numerous usable elements with evidence and lessons from existing schemes, particularly US EPA rail, that will help inform the development of a GB rail emissions mitigation testing protocol. The following key learnings have been identified in a review of relevant current emissions mitigation approval schemes.

- Successful expectations of emission reductions need to match the drive cycles in real world use and the capabilities of the technologies under consideration
- Differences between testing and real-world drive cycles can lead to smaller reductions for certain applications
- A ‘one size fits all’ approach is not suitable for the range of NRMM activities; a sector-based approach can be more effective
- Durability has a large, mostly hidden impact on real-world emissions
- While reductions over time in US certification requirements appear smaller compared to European emissions standards, the real-world impact is much greater since the US approach pays much closer attention to actual drive cycles
- A greater cumulative impact on emissions can be achieved by retrofitting older existing engines where practical rather than making limited improvements to newer rolling stock that already have comparatively low emissions

- For retrofit kits, it is important to carefully specify parts (and designs) so *what was tested* is *what is supplied*
- The US rail approach is not just focused on direct emission reductions from mitigation solutions but also encourages emissions reduction at low engine powers due to better efficiency. Such improvements can be captured by the US testing methodology.
- Mandated retrofits in the US for stationary reciprocating internal combustion engines (RICE) focused on reasonably sized and easy reductions under a wide range of conditions and not on a target percentage or metric. Since known, robust technologies were used no end-user testing was required.
- US states have focused on addressing local air quality problems, by requiring rail operators to use electric or low emissions locomotives, or by addressing other sources such as container handling equipment in yards
- The California Air Resources Board has enabled a number of initiatives, including funding research and development to assess emissions reductions and reliability of mitigation solutions. Long-term real-world usage trials can identify issues before large-scale deployment.

The emissions both before and after changes based on real-world drive cycles for most rail emissions mitigation solutions are often likely to be smaller than claimed in other sectors. Therefore, it would be more sensible to plan for smaller but realistic and achievable emission reductions, while also ensuring sufficient emissions durability, i.e. emissions do not degrade significantly over a realistic period of time.

Existing retrofit schemes are largely based on engine or abatement changes, but the technical landscape is changing with hybrid or battery options becoming increasingly available and affordable. Ensuring that mitigation solutions that involve shut-down of the engine, particularly in key locations such as enclosed stations, are fairly considered will be an important consideration.

An emissions mitigation approval scheme for GB rail should include the following attributes:

- It needs to be able to assess emissions before and after installation for all realistic mitigation measures
- It should be based on real world drive cycles that reflect the expected conditions experienced by particular rolling stock on relevant services
- Such drive cycles may change substantially as a result of the installation of the mitigation solution, for instance more time in higher engine powers when the engine is running but also significant time when the engine is shut off. Sufficient information (at multiple test points) should be collected to ensure the full emissions reductions can be modelled and understood.

- US Rail and Euro VI HD weighting maths should be used to ensure the time in and emissions from idle are understood and addressed
- It should not be dependent on a single metric (e.g. g/kWh) but require the consideration and evaluation of individual test modes.

4 Off-Engine Measures

4.1 Background

Whereas the previous sections have focused on measures that can be implemented to reduce emissions at source, through either in-engine measures or exhaust after-treatment, this section turns the attention to 'off-engine measures'. These encompass any procedure, measure or device with the potential to deal with emissions and/or reduce human exposure after they have already been released from the train and into the station environment. Three main approaches will be addressed in this section: keeping exhaust fumes away from people; improved ventilation; and off-engine mitigation measures.

Especially in recent years, there has been an increased interest in and awareness of air quality, its health implications, and its sources. This has led to an increase in the availability of devices designed to improve air quality in different settings. Therefore, it is important to assess these options for their use in rail and determine their applicability to this sector. Guidance has already been created to understand mitigation measures that can be taken to limit the exposure of residents to air pollution (IAQM, 2019) and for student's exposure in schools (The Mayor's School Air Quality Audit Programme, 2018; Kumar et al., 2020). These guidance documents, often cover both how to reduce emissions from the source, and how to reduce exposure. However, the environments covered in these guidance documents, residential dwellings and schools, are very different to rail environments which pose very different challenges. Therefore, this document aims to consider these challenges and provide guidance for enclosed and semi enclosed station environments.

Since the COVID-19 pandemic commencing in 2020, the air quality on trains for passengers has been of interest to many in the rail industry. A research project was commissioned by RSSB in 2021 entitled "CLEAR: Air Quality on Trains-HVAC and Exhaust Interactions Study (T1234)" to investigate the improvements that could be made to onboard heating, ventilation, and air conditioning (HVAC) systems for improved air quality. There are several stages to improving onboard air quality, the first being to simply reduce the emissions produced by the engine in the first instance. T1234 focuses on the second stage, which is reducing the amount of pollutants entering the train carriage once they have been emitted by the engine. This may involve considering the aerodynamics to reduce the amount of quantity of the exhaust fumes that subsequently enter the HVAC system. It also may involve improving the efficiency of the air filtration in the HVAC systems to remove a larger amount of the PM, including droplets which may potentially harbour and transport the COVID-19 virus according to recent studies (Comunian et al., 2020; Nor et al., 2021). However, a major barrier exists when it comes to the efficiency of the PM filters that can be fitted in the HVAC systems. Usually, a well is recessed into the roof for the HVAC (a smaller version of the pantograph recess well) for the purpose of bringing air into the HVAC and for expelling air. More efficient filters will usually require more space because of the greater number of filtration layers, and this need for more space is a major constraint. In addition, increasing the efficiency of the filter often leads to an increased pressure drop within the device, resulting in a reduction in the air flow through the HVAC system. A greater power supply is therefore required to compensate and maintain the same air flow rate. Most train HVAC motors do not have sufficient power for this. Furthermore, onboard filtration systems usually only reduce PM concentrations with little to no impact on NO_2 concentrations. Although onboard pollutant concentrations are an area of active investigation, they will not be discussed further in this report which will focus on addressing concentrations and pollutant exposure in railway stations.

The aim of the sections that follow is to provide a guide for the rail industry, identifying both the benefits and the limitations of each off-engine measure or device found from a literature search and consultation with experts.

4.2 Assessment criteria

A literature review has been carried out to find a variety of off-engine mitigation measures used in rail. This involved directly searching sites such as researchgate.net and PubMed for references to such mitigation measures and their efficacy, as well as the use of search engines. In addition, key industry contacts were approached for any relevant knowledge or insight they had.

Consideration has also been given to devices still in their research phase, as well as commercially available products.

Each off-engine mitigation measure has been considered holistically for their practical use in an enclosed station environment. The assessment criteria that each measure has been considered against are:

- **Effectiveness of AQ exposure reduction:** assessed by the percentage reduction in a given pollutant's concentration as a result of the measure, ideally at the location where pollutant exposure will occur.
- **Scalability to Rail:** this refers to whether a measure will be able to treat the amount of emissions to make a meaningful impact on air quality in stations, such as the volume of air a device may process per hour.
- **Applicability:** if the device or measure has not been tested in a station environment, this criteria concerns how applicable the results of current studies are to such a context.
- **Commercial Feasibility:** the anticipated cost of the mitigation measure.
- **Long Term Sustainability:** whether the measure is likely to cause an increase in greenhouse gas emissions.

- **Operational Feasibility & Technical Practicability:** the feasibility of installation of any device or the difficulty of implementing a measure as well as the likely maintenance a device may require.
- **Customer Perspective:** how members of the public are likely to perceive each mitigation measure.
- **Independently Assessed:** whether an independent assessment of a device or measure has been carried out by a third party for its effectiveness.

To provide an overview of the detail provided in this review, a characteristics matrix is presented in Section 4.5 with each off-engine mitigation measure assessed against the above criteria.

4.3 Key issues and constraints

A key and persistent challenge during this review was the lack of independent, peer-reviewed studies into station specific mitigation measures or devices. Where no such studies exist, information has been gathered from press-releases, newspaper articles, or through direct discussions with rail industry contacts. A lack of independent assessment of a given device has been highlighted in Table 3 as this is an important indicator of a device's reliability. In addition, information on air pollution mitigation measures and devices deployed in non-rail contexts has been gathered, with the applicability of the measures to the station environment assessed. Where data does not exist, expert judgement has been used to provide estimates.

When assessing a measure's impact on air quality exposure, PM and NOx have been considered separately. The latest Transport Analysis Guidance data (Department for Transport, 2021) suggests that the proportions of the air quality burden for rail regarding damage costs is around $7/8^{th}$ NOx and $1/8^{th}$ for PM, whereas for road transport the damage costs are closer to 50% each. Significantly more research has been done into mitigating the air quality impact of road transport, but this discrepancy in pollutant impact between the road and the rail sector demonstrates that a different approach must be taken for rail. A much greater focus must be placed on how to tackle NOx emissions when considering the rail sector. Unfortunately, however, most devices are specifically designed to reduce PM only, with marginal or no impact on NOx concentrations.

4.3.1 Thought experiment: Marylebone Station

To understand the specific challenges relating to the station environment, we consider Marylebone station to be a good example of a semi-enclosed station with elevated pollutant concentrations. We will therefore set out the specific characteristics of Marylebone, and the trains which idle at its platforms, and their effect on pollutant levels and how effective different types of mitigation measures may be in a thought experiment.

By considering the likely engine running times of the trains at Platforms 1, 2 and 3 at Marylebone, the pollutant emission factors and rates, the estimated emissions input into Marylebone is 2,123 g/hour of NOx and 24 g/hour of $PM_{2.5}$ at peak times[3]. These emission inputs would lead to much higher pollutant concentrations than those actually measured inside Marylebone station[4], which suggests that the majority of emissions are dispersed out of the station via the limited natural ventilation in the station. The remainder of these emissions are prevented from dispersing into the ambient air by the fact that the station is semi-enclosed, containing a volume which is approximately 90,000 to 100,000 m^3. This provides an insight into the volumes of air inside a station which must be treated to reduce pollutant concentrations. Clearly, the issue of scalability arises, as most filtration devices on the market are primarily designed for residential or office use. A room in a dwelling has a volume of air approximately 250 m^3, therefore it is evident that a device designed to function effectively in this environment is unlikely to process the volumes of air needed to make a noticeable difference to air quality in a station. A measure or device may therefore be an effective pollutant filter when comparing the pollutant concentrations in the input and output air, but if it cannot filter enough air fast enough then it will not be an effective mitigation measure overall. This is particularly pertinent to the station environment, as the polluting diesel engines provide semi-continuous emissions into the air in the station. Therefore the assessment criteria of **scalability to rail** was introduced, as a way of accounting for this discrepancy.

The enclosed or semi-enclosed nature of many stations leads to insufficient natural ventilation. As a result, perfect mixing of air is not achieved due to inadequate circulation. Even if a device was claimed to process 3,000 m^3 of air an hour, if 30 such devices were installed in Marylebone Station they would not be able to filter the air of the entire station for pollutants efficiently. In addition to this, a summary of ventilation actions to mitigate the risk of COVID-19 by the SAGE Environment and Modelling Group (2020) recommends six air changes per hour in order to reach a 95% removal of air contaminants in 30 minutes. To achieve this, roughly six times more of these example devices would need to be installed at Marylebone, assuming these devices were effective at removing COVID-related pathogens. Further internal air circulation would therefore be needed in order for such air filtration devices to have even a minor reduction on overall station pollutant concentrations, increasing the cost and reducing practicality.

A device that can process a few thousand m^3 of air an hour may, however, be able to have a meaningful impact on the quality of air in designated waiting rooms, as defined by the Offices, Shops and Railway Premises Act (HMSO, 1963). Waiting rooms are self-

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[3] Off-peak emissions input is assumed to be 72% of these values. Calculations performed take both stationary idling, and idle during coasting/braking into account, as well as Notch 4.

[4] Monitoring occurred during a previous RSSB project (RSSB, 2021) with NO_2 concentrations ranging from 140 – 160 µg/m^3, and PM_{10} ranging from 20 – 40 µg/m^3. 65% of PM_{10} was measured to be $PM_{2.5}$.

contained rooms, closed off from the rest of the station by doors. They will therefore contain a much smaller volume of air than an entire station concourse. With passengers frequently entering and leaving a waiting room, the mixing of air within the waiting room is also anticipated to be great enough to prevent the pollutant reduction effect of the devices just being highly localised to the devices themselves.

4.4 Assessment of Options

All off-engine measures and devices have been split into three different groupings: keeping members of the public away from the sources of emissions; improved ventilation; and off-engine mitigation. Each measure or device has been assessed against the criteria stated in Section 4.2.

4.4.1 Keeping Members of the Public Away from Emissions

This grouping of measures concerns keeping the public and station staff away from the emissions source as much as possible to minimise their exposure to high levels of pollutants as far as possible. This could involve increasing the distance between members of the public and the pollutant source, as pollutant concentrations fall off with distance from a source. Alternatively, measures could be implemented which create some kind of barrier between the emissions source and the areas where members of the public will be present.

4.4.1.1 Barriers

Non-porous, solid barriers can disrupt airflow between the emissions source and the locations where members of the public are likely to spend the most amount of time. Most studies of the implementation of barriers to reduce air pollutant exposure have evaluated projects to mitigate road traffic emissions, where barriers were placed between the source (road vehicles) and sensitive receptors such as pedestrians or dwellings. Placement of barriers must be considered carefully, as the concentration of pollutants is likely to increase on the barrier side closest to the source due to restricted dispersion. However, a study by Baldauf et al. (2016) on the use of noise barriers to mitigate air pollution along stretches of a highway in Arizona, considered pollutant concentrations on the side of the barrier closest to the road. Measurements performed did not show increased concentrations of pollutants on the side of the barrier closest to the road when compared to ambient concentrations.

Roadside studies have generated a range of conclusions. The Arizona study measured NO_2 and black carbon reductions of up to 41% and 63% respectively when the noise barriers were installed, although maximum reductions were measured at a distance of between 50-150 m from the barrier. In a station environment, members of the public will likely congregate only a few metres from the train on the platform. Therefore, such large pollutant reductions may not be experienced by many members of the public in stations.

An earlier study (Baldauf et al., 2008) measured concentrations of CO and PM behind roadside barriers next to a highway in Raleigh, North Carolina. The study showed that the concentrations of these pollutants behind the barriers were highly dependent on meteorological conditions, with concentrations even being higher behind the barrier than on the road side of the barrier when the wind was directionally toward the road. It is worth noting that this study took place along a highway in a flat area that, aside from the presence of the noise barriers, was free from roadside obstructions that would disrupt the flow of air and therefore the upstream airflow is likely to be laminar as it approaches the barrier. In an enclosed station environment the airflow is highly unlikely to be laminar close to any platform barrier, making it hard to directly apply the results of this earlier study to rail. However, what this study does show, is that the concentrations that can be measured behind a barrier are highly dependent on the direction of airflow and therefore barriers should not be installed in a station without a solid understanding of the average flow of air within the station. It is worth noting that measurements performed as part of the later study (Baldauf et al., 2016) did not find increased concentrations behind the barrier.

The roadside barriers used in the Baldauf et al. (2008, 2016) studies were 4.5 m in height and 1 m in width for the 2016 study, and 6 m in height in the 2008 study (where a width was not provided). The barriers were also placed 3 m from the kerb and 5 m from the kerb in the 2016 and 2008 studies, respectively. These dimensions would be completely impractical for station implementation as the minimum platform width allowed is 3 m for a single face platform or 6 m for a double face platform, although this is also dependent on train speeds (RSSB, 2018). Stations with significant passenger numbers must, however, have wider platforms to ensure a maximum passenger density on platforms can be met. With these barrier heights, any barrier used in a station would have to be transparent to allow members of the public to view information displayed on the front and side of the train body.

Highways England produced a summary report of research projects intended to improve air quality along the strategic road network (Highways England, 2019). In this report, no impact on the pollutant concentrations were measured for barrier heights of 4-6 m. However, reductions in NO_2 concentrations were measured when the barriers were 9 m tall. Highways England also studied the use of mineral polymer barriers, coated with a material designed to remove NO_2 from ambient air. In laboratory conditions, the mineral polymer coating had removed a large amount of NO_2 in a short period of time. However, in the roadside study, tested in real world conditions, the polymer material was not effective at removing NO_2.

The above studies all consider roadside barriers, and therefore caution must be taken before applying any of the conclusions to a rail setting. Most notably, it is unclear whether the effectiveness of the barriers will be upheld in the geometrically different environment of a platform when compared to at the roadside; platforms are raised above the tracks, producing a gap of just over a metre which will undoubtedly impact airflow and thus concentration distribution. Additionally, exhausts on diesel trains are positioned on the top of the train, causing the plume of the emissions to be vastly different to that of road vehicles where the exhaust is typically closer to the ground. This height variation and the impact it will have on the vertical concentration gradient is not covered by the studies of roadside barriers. Similar vertical barriers would therefore likely be required be at least as tall as the position of the train exhaust, if not taller.

Therefore, to ensure that the emissions from the train exhaust do not simply disperse over a straight, vertical barrier installed at the platform edge, platform edge doors could be installed (PEDs). This solution is already being used in the transport sector, commonly used in underground railways in many countries. Although these are primarily deployed as a safety measure, they would also potentially reduce dispersion of train emissions to prevent pollutant concentration build up for those on the platform or concourse. This measure would consist of a barrier from platform edge to the stations ceiling above composed mostly of acrylic glass with automatic doors which open to allow members of the public to pass through. Where there is a large distance between the train and the ceiling in a train shed, the PEDs could instead theoretically take the form of an acrylic glass “tunnel” placed over the tracks. However, such an installation would require frequent cleaning to prevent dirt building up on the inside walls of the tunnel. A paper by Wen et al. (2020) on underground railway ventilation suggested that platform edge doors could be an effective measure to limit internal sources of pollutants from members of the public, though this study only considered underground railway environments which vary considerably from enclosed rail stations in their geometry. A study (Son et al., 2013) on the effect of PEDs on PM_{10} levels in underground railway stations in South Korea demonstrated that the installation of PEDs resulted in the concentrations measured on the platform being lower than those of the ambient air, whereas for platforms without PEDs the concentrations measured on the platforms were higher than those of the ambient air. However, the PEDs also had the consequence of significantly increasing the concentrations of PM_{10} inside the tunnels due to reduced dispersion into the surrounding volume of air contained within the internal underground railway structure. If such a measure were to be deployed along a train track adjacent to a platform, then this may result in any onboard passengers being exposed to high pollutant concentrations whilst a train is idling.

Placing PEDs in a rail station would pose challenges that do not exist for underground railway stations. Firstly, as underground railway trains are electric, they do not have exhaust fumes that would be being emitted while at the station platform and therefore some PEDs in this environment have overhead venting. If PEDs were used to reduce dispersion of diesel emissions in train stations, they would have to therefore be fully enclosed without overhead venting to prevent exhaust fumes dispersing out of the top of the PED and onto the neighbouring platforms.

The biggest limitations to PEDs installation in a train station are practical ones. Underground railway trains are all a standard size making the dimensions of the PEDs and their automated door placement simple. This is not the case for rail as there is no common fixed door spacing, with different rolling stock types having significantly different door placements, and the end and intermediate vehicles in DMUs are different lengths. This would make deciding where to place the automated doors on the PED impossible unless the entire rolling stock was replaced, as the train carriage door and the PED would have to perfectly align. Even if a perfect PED door placement could be achieved, aligning the train carriage doors with the PED openings requires precision stopping that no diesel rolling stock worldwide is capable of, and even then would require the instalment of very expensive signalling systems to achieve the accuracy required.

As PEDs are already a familiar sight to most people who frequently use underground railway systems, they may be a more accepted mitigation measure if installed in rail stations. PEDs cost approximately £7,000 per metre. However, PEDs come with significant challenges that will be very difficult to overcome, with the additional risk of increasing pollutant concentrations for those onboard the train carriages.

4.4.1.2 Boarding Areas

A simple solution, where the environment permits it, is to physically keep members of the public away from areas of the station with high pollutant concentrations. Similarly to airports, train stations could be zoned, with members of the public discouraged or not allowed onto platforms unless train boarding or off-boarding was taken place. Many guidance documents detailing mitigation options for reducing exposure to pollutants in schools and nurseries suggest a variety of measures that work to increase the distance between students and sources of emissions and reduce their time at locations of poor air quality. Guidance produced by the Global Centre for Clean Air Research suggests that local authorities create controlled parking zones in the vicinity of schools which increase the distance between idling vehicles and students arriving at or leaving the school premises (Kumar et al., 2020). Likewise, The Mayor's School Air Quality Audit Programme lists a variety of measures that could be deployed in schools to increase the distance between the emissions source and students, such as relocating pedestrian entrances away from roads where cars idle, and relocating playgrounds and "free-flow" spaces (The Mayor's School Air Quality Audit Programme, 2018).

A study (Hickman et al., 2018) measured the concentrations of NO_2 at Birmingham New Street with diffusion tubes where monthly average concentrations peaked at just over 500 $\mu g/m^3$ on the platforms. Although measured concentrations were significantly less in the waiting lounges, they still exceeded 300 $\mu g/m^3$ at two of the three lounges. Concentrations outside the station are significantly lower than inside the station, averaging at 62 $\mu g/m^3$ during the sampling period. This demonstrates that the introduction of clearly defined "waiting zones" can go some way as to reducing exposure to pollutants, but may not solve the problem of unsafe exposure levels on its own. In contrast, computational fluid dynamics modelling carried out by Airlabs (2020) showed that the highest concentrations of NO_2 on the concourse at Marylebone station are actually greatest at the furthest point from the train shed due to the airflow within the concourse. This shows that the success of this measure in reducing pollutant exposure is highly dependent on the dimensions and shape of the station interior, its airflow, and the emissions input to the station.

This measure would undoubtedly require significant support from train station staff to ensure compliance which could increase the cost of the measure, as well as any necessary changes to station infrastructure to allow zoning to take place. Such a measure will most likely pose difficulties to both smaller stations with limited space and larger stations with heavy footfall to accommodate the appropriate number of customers.

Encouraging members of the public to crowd into "waiting zones" before boarding a train may also increase the levels of PM in those areas. Overcrowding has been linked to worse air quality, likely due to increased activities causing resuspension of PM into the air (Sá et al., 2017). However, the positive impact on pollutant exposure reduction from this measure is likely to be much greater than the potential impacts of resuspension.

4.4.1.3 Air Curtains

Air Curtains are devices which provide a continuous stream of downwards air blown from the top to the bottom of an open doorway. This stream of air is designed to disrupt the normal airflow through the doorways, helping to create two separate environments on either side of the door. Therefore, air curtains could be installed in the doorways between areas of a station, for example in the doorway into a waiting room, to limit the dispersion of emissions into these environments.

Primarily, air curtains exist as an effective measure to control airflow, with the added benefit therefore of also helping to control temperature between two environments with the downward stream of air creating a barrier. Therefore, air curtains are likely to also maintain a more comfortable environment for customers in waiting rooms.

However, air curtains can consume a lot of energy when ambient temperatures are low if the air curtains are also intended to maintain a temperature gradient. It is also worth noting that air curtains are less effective when the doorway they are above is frequently used and they cannot block excessive drafts, for example an incoming wind speed of 3 m/sec is considered the maximum speed before the air curtain can no longer maintain two distinct environments (Building Services & Environmental Engineer, 2013) . The velocity and the momentum of the jet needs to be tailored to prevent "short throw" or "excessive throw" - the former will do little to reduce dispersion through the air curtain and the latter can make air quality worse close to the air curtain. This is because excessive throw leads to turbulent flow, resulting in the air curtain stream partially mixing with outside air which in turn reduces efficiency.

The costs of air curtains vary depending on the velocity of forced air, the size of the doorway it is designed to cover, and whether or not it is also required to heat the air. The cost of high velocity air curtains designed to cover larger doorways are typically priced between £1,000 and £2,000. Energy savings in commercial buildings exceed 30% when using air curtains as they reduce the need for expenditure on maintaining comfortable indoor conditions using other methods (Gil-Lopez et al., 2013), although the study which demonstrated this was performed in the East of Spain where climatic conditions vary significantly to those in the UK. Most air curtains can also be fitted with filters to remove pollutants from the air being sucked in by the device, although this may make maintenance tricky as the filters will need to be frequently replaced which can cause issues with the devices typically being installed above busy, frequently used doorways. Most of these filters also only work to reduce PM emissions. A case study produced by Berner International Corporation covered the installation of air curtains at an industrial parts manufacturer as an energy efficiency measure that also resulted in improved air quality by fitting off-the-shelf filters into the device (Berner International Corp.). Although pollutant concentrations were not measured before and after, the pollutant induced haze in the facility has gone and the plant's chronic asthma sufferers reported significant breathing improvements.

4.4.1.4 Changes to Train Flows

It is undoubtable that pollutant exposure would decrease in stations if there were fewer diesel trains at stations as they are a large contributor to pollutant concentrations. Train flows could be changed to place caps on the number of diesel trains entering a particular stations during a given period of time, with the remainder of trains having to be fuelled by alternative means. Equally, the cap could be abatement specific, where, for example, only trains with the ability to idle whilst purely powered by battery would not be affected by the cap. If the frequency of diesel trains at "problem stations" could be reduced in this way, the reduction in concentrations in stations would be very significant to the extent that this is likely to be the mitigation measure able to cause the greatest reduction in exposure to pollutants (both PM and gaseous pollutants alike), as well as a significant reduction in the CO_2e emitted by the rail sector.

There is a small amount of precedence for this option as a mitigation measure already. In 1908, New York rail enforced electric only train operation in either tunnels or terminals for both passenger and freight trains in Manhattan. For the road transport sector, many guidance documents designed for school air pollution mitigation also recommend staggering drop-off or pick-up times to reduce the number of idling road vehicles in a given time period (The Mayor's School Air Quality Audit Programme, 2018; Kumar, et al., 2020). Such a measure would require significant local if not national level coordination to change train flows, and would require adjustments to be made to routing and train timetables. The associated cost of such an intervention is expected to be extensive.

4.4.1.5 Mandatory Face Masks

Since 2020, the general public of the UK has become familiar with mask wearing, a measure that has already been used extensively throughout the world, particularly in parts of Asia, as a personal strategy to reduce pollution exposure. Although face masks have no impact on reducing the exposure to gaseous emissions, face masks could be made mandatory at train stations in order to reduce exposure to PM. However, the reduction in black carbon greatly varies between the types of masks worn and how they are worn, with one study showing the percentage reduction in black carbon to be between 3% and 68% (Carlsten et al., 2020). The same study measured reductions of 15% in particles similar in size to typical diesel engine fumes when an individual was wearing a cloth mask.

This measure will likely prove to be unpopular by members of the public due to the association between mask wearing and the COVID-19 pandemic. Furthermore, such a measure would shift the burden of responsibility from the polluter to individuals affected by the pollution, drawing attention to rail emissions and potentially deterring people from using rail. As a result, it is anticipated that mandatory mask wearing would prove to be a very hard measure to enforce. Concerns have also been raised about the potential for disposable face masks to contribute to microplastic pollution, therefore encouraging their adoption as an air pollution exposure reduction measure may result in greater exposure to other types of pollution, as well as damaging marine life (Abbasi et al., 2020; Dharmaraj et al., 2021).

4.4.2 Improved Ventilation

4.4.2.1 Built-In Natural Ventilation

Recently built or renovated stations, such as London Bridge or Worcestershire Parkway with open-air platforms, are designed with natural ventilation in mind to prevent the kind of concentrations that occur in semi-enclosed or enclosed stations. Increasing station ventilation can aid air pollutant dispersion, preventing the build up of air pollutant concentrations. Despite being an area predominantly served by electric multiple units, there are instructive learnings from how exhaust emissions from diesel trains have been handled at key South London termini. When the shopping centre and offices over the central and western concourses and platforms at Victoria Station were built in the mid-1980s, extraction fans were installed over Platforms 18 and 19. However, when the Class 205 trains were later replaced in 2003-4 by Class 171 trains the fans were no longer located directly above the train exhausts and thus all regular diesel traffic from the Uckfield Line was required to use London Bridge. Furthermore, prior to rebuilding, Uckfield trains used the fully open-air Platform 8 at London Bridge whenever possible (typically off-peak). With all six terminating platforms now open air this operational restriction has been removed.

The placement and type of natural ventilation can have unexpected and unintended impacts on airflow within the station. CFD modelling of the airflow in Marylebone concourse has been carried out by Airlabs (2020), which demonstrated that the highest concentrations of NO_2 are predicted to occur at the southwest corner of the concourse, even though this is not the closest part of the concourse to the source of emissions i.e. the diesels trains in the platform area of the train shed. This is likely due to the placement of doorways and that the open end of the train shed provides ventilation, which affects the airflow throughout the concourse. It is vital that any measures with the potential to change the circulation of air in a station seriously consider how the airflow might be impacted, and ideally model this using computational fluid dynamics.

One option for natural ventilation would be roof vents. When emissions have just left the engine exhaust they are hot and therefore less dense than the surrounding air, causing these emissions to initially rise to the roof. Therefore, the easiest time to implement ventilation will be at this point by improving ventilation in the roof above the exhaust, preventing the emissions from being dispersed around the enclosed station. Of course, such a measure may not be possible for all stations depending upon their infrastructure, and especially if they have listed roof structures.

Ventilation must be designed to take into consideration meteorological conditions. For most locations across the UK, the prevailing wind comes from a south-westerly direction, but in the spring time especially there are an increased number of incidents of differing wind direction (Lapworth and McGregor, 2008). The prevailing/predominant wind speed and direction are also highly dependent on location, affected by local topography – for example, the Keswick meteorological station measures a large component of the wind as coming from the easterly direction. If a ventilation system is designed to suck ambient air in from outside the station aided by the average wind direction, then it must also be designed to work when the wind direction varies. Care must be taken for the pollutant concentrations inside parts of the train shed to not be made worse when the wind direction is, say, from the northeast.

Increasing natural ventilation by providing vents, changing roofing tiles, or keeping doors or windows open can reduce the comfort of members of the public particularly in the winter. In stations, designated waiting rooms, closed off with doors, are heated and therefore increasing natural ventilation may lead to an increased cost of heating. In addition, increasing ventilation may also lead to increased pollutant concentrations in waiting rooms due to ingress of external pollutants.

4.4.2.2 Emission Extraction Systems

Mechanical ventilation systems can be used to try to remove emissions from the train shed to the ambient environment. Birmingham New Street station contains a system with 98 bi-directional jet fans across 12 platforms which were originally controlled by an array of CO_2 sensors. In 2019, the fume extract system underwent enhancement, with 103 NO and NO_2 sensors being installed with associated 8 speed fan control. The enhancement occurred due to studies showing that high concentrations of CO_2 do not necessarily correlate to high concentrations of NO_2 (Hickman et al., 2018). Additionally, new Workplace Exposure Limits were introduced in 2018 by the Health and Safety Executive (Health and Safety Executive, 2018), with NO and NO_2 concentrations in Birmingham New Street exceeding the 15-minute exposure limit on most days before the fan system was upgraded with additional NOx sensors (Thornes et al., 2021). New air pollution data in 2020 revealed that NO_2 concentrations in Birmingham New Street decreased by 23-42% compared to monitoring undertaken in 2016 and 2017, mostly attributed to the upgraded fan system effectiveness (Clegg et al., 2022). This latest data shows that concentrations of NO_2 are now below the occupational health standards, but are still exceeding EU public health standards at the station. This is unsurprising, as the station has unique underground geography which traps emissions from the approximately 600 diesel train movements that occur within the station each day, representing about half of all train movements in the station (Thornes et al., 2021). This upgrade of the emissions extraction system cost over £750,000.

When using bi-directional fans such as those used in Birmingham New Street, reliable and permanent sonic wind sensors should also be installed to control the ventilation system automatically. This is because the direction of the fans need to be carefully aligned with the wind direction so that the fans blow in the direction of the wind rather than against it. Any turbulence introduced by high wind speeds, or otherwise, will reduce the efficiency of any extraction system.

The type of extraction system fitted will also be highly dependent on the station environment. All five of the train depots for GWR have extraction systems, but each system is very different to compliment the depot environment and its associated challenges. For example, in the Exeter GWR depot, after CFD analysis of the train shed was undertaken, 48 radial duct fans were fitted in the ceiling to achieve eight air changes per hour, triggered by 148 sensors. This system is appropriate for the space as there is very clean roof space in the train shed, resulting in significant airflow capacity. In contrast, the ceiling at the Reading depot contains a lot of ducting and lots of containments such as pipework, which encourages turbulent flow in the roof space making achieving laminar flow difficult. This lack of laminar flow makes the extraction of fumes by the ten fans in the ceiling less efficient. As a result, only two changes of air occur per hour can be achieved in this depot, as the turbulence is too high when the velocity of the fans is increased too much. The Reading depot also has “dead spots” of fume build up at central points in the long train shed which contains three roads. These were discovered by extensive continuous monitoring at stationary locations in the shed but also by placing monitoring devices onto those working in the shed and are likely occurring due to this lack of laminar flow in the shed. Attempts are being made to increase the amount of fresh air coming into the shed by the use of pumps to try to deal with these dead spots.

Emission extraction systems can also be extremely noisy; the system implemented at Birmingham New Street has received several noise complaints. Similarly, the extraction system installed at the GWR depot in Penzance could initially be heard by residents in the local town over 2 miles away. The system there consists of six axial pitot tube fans which were originally operating to achieve six air changes an hour, but the speed of the fans had to be reduced to decrease noise pollution after noise complaints were received. Decreasing the speed, however, increased pollutant concentrations in the train shed and therefore attenuation was fitted on the outside of the fans and weather grills/baffles were removed. Despite these measures, breakout noise still occurs from the fans inside the shed.

Significant challenges exist when using sensors to trigger an extraction system. Most will need to be regularly calibrated which can be a time-consuming task due to the high number of sensors required for an effective extraction system. The settings chosen for the system will also be highly dependent on the environment, and a level of experimentation will be required to achieve optimum operation. In the Penzance GWR depot, the fans come on at a low rate at 8:00 pm (most depot activity occurs at night) with the rate of operation increasing based on the continuous monitoring data from the sensors. Settings can also be changed to ensure that the fans operate when the train drives past a wheel mounted mechanical trigger, and 40 minutes after this trigger has occurred the system reverts back to sensing. In the Exeter depot, however, the fans are purely triggered by the depot protection system (DPS) before modulating after 40 minutes and do not start with an initial lower rate like at Penzance. Care must be taken to protect sensors and keep them clean to allow them to keep operating efficiently. If the sensors get wet from rainwater then the moisture will collect contaminants, giving false readings.

Rather than basing the extraction system around ceiling fans, other methods can be used. The GWR depot outside of Bristol uses extraction nozzles on a mechanical arm which find the exhaust automatically and place the nozzle over it. Due to the high number of footfall at train stations, there is a risk of such a device getting damaged if used in a station, or of it injuring people as it moved to find the exhaust. This depot also deploys a long hood made of a lightweight fabricated design which is designed to cover the entire length and width of the train, trapping fumes so they can be sucked out. However, when the engine is running too quickly the gases often roll around the hood and escape out the other side due to turbulence. The extraction velocity is simply not sufficient to deal with the velocity of the gases coming out the exhaust. Therefore, GWR are exploring hybrid options to either upgrade the hood with a bulbous design to provide a wider catchment area for the fumes, or by also supplementing the entire train shed with more fans.

A downside of increasing ventilation, whether natural or mechanical, is that emissions are not reduced – they are simply moved from one location to another. If residential dwellings are in the immediate vicinity of the station, care must be taken to ensure that any station extraction system does not result in those residents being exposed to unsafe concentrations of pollutants. The extraction system at Exeter GWR depot has had issues with diesel exhaust going into the neighbouring accommodation block when the settings of the sensors were not optimised. Emissions extraction systems also consume a lot of energy, especially if near continuous use is required to achieve safer pollutant exposure. This leads to an increased carbon footprint of the depot, as well as increased costs due to the energy required.

4.4.3 Off-Engine Mitigation

This grouping of measures covers devices designed to "treat" the emissions once they have left the source. This could occur through chemical, mechanical, or electrostatic interactions designed to control pollutant concentration levels.

4.4.3.1 Urban Vegetation

The introduction of vegetation has become an increasingly popular method for mitigating air pollution. Many guidance documents for improving air quality suggest using vegetation (The Mayor's School Air Quality Audit Programme, 2018; Kumar et al., 2020), and some studies have considered its effectiveness at mitigating against road emissions for pedestrians. One such study focusing on street canyon environments found that poor green infrastructure can lead to an accumulation of pollutants at pedestrian level due to reduced air exchange between air above and within the canyon (Tomson et al., 2021). Similarly, the effects of vegetation on airflow must also be considered in a station environment. The same study also showed that continuous hedges without gaps were the best at reducing pedestrian exposure but must have a minimum thickness of 1.5 m and a minimum height of 2 m which will be impractical if deployed in a station environment between the trains and the platforms. Another study of $PM_{2.5}$ deposition involved modelling using ENVI-met, where the combined use of green roofs and walls was modelled to remove up to 7.3% of $PM_{2.5}$ (Viecco et al., 2021). This study, however, was carried out in a Mediterranean climate, with climatic conditions known to impact deposition – for example, higher levels of precipitation reduce the amount of resuspension of PM and therefore increase leaf deposition. Meteorological conditions can also impact the effectiveness of vegetation, with another study suggesting that the orientation of vegetation with respect to airflow direction can lead to both the increase and the decrease of pollutant concentrations – for example, trees which are planted obliquely to the prevailing wind direction can increase pollutant concentrations by up to 225% (Abhijith et al., 2017). The same study suggested that the percentage reduction in pollutant concentrations when using green walls could be between 0% and 95% through modelling depending on the orientation of the green wall. However, a paper by the Defra Air Quality Expert Group (AQEG), which undertook an in-depth review of the available literature, concluded that reductions quoted in some papers were questionable. AQEG's calculations determined that concentration reductions of PM would only be about 2-10% with very ambitious planting scheme using trees (AQEG, 2018). For practical planting schemes using hedges, the reductions would be even less.

The Greater London Authority (GLA) report on green infrastructure as a mitigation measure against air pollution mostly focuses on reducing exposure to road emissions (2019). Although at a national scale deposition plays a vital role in reducing concentrations of air pollutants, the report concludes that at a very localised level the importance of vegetation is its ability to affect dispersion. As a result, to achieve maximum pollutant exposure reduction, the recommended type of vegetation, and the vegetation's placement, will be highly dependent upon the location. For example, the report recommends a dense avenue of trees for street canyons with little traffic but recommends a hedge or green wall for canyons with heavy traffic when the height to width ratio of the canyon is less than two. Therefore, before vegetation is introduced to a station environment for the purposes of pollutant exposure reduction, it is important to understand the geometry of the space and the airflow within this space.

The type of vegetation used also has a major impact on the pollutant reduction, with leaf features such as grooves, ridges, trichomes, stomatal density and epicuticular wax amount increasing PM capture (Tomson et al., 2021). A study that explored PM capture rates at nine different sites across different level of "urbanisation" in Australia found that moss captures 3.8 times more PM than tree species (Haynes et al., 2019). In high urbanised environments, the moss captured 25.29 mg of particulate matter per g of moss, but mostly what was captured was PM_{100}, i.e. the coarse fraction of PM, which is not as directly linked to health impacts as the finer fraction of PM (Anderson et al., 2012). Another study has found that the majority of PM deposited onto leaves is resuspended into the atmosphere, washed off by the rain, or dropped to the ground which occurs at a faster rate with increased wind velocity (Hartig et al., 2014).

Vegetation is not an efficient sink for NOx and extensive planting is required for a noticeable reduction in PM due to lack of air volume to vegetation surface contact. Jones et al. (2017) suggest that total existing UK vegetation had no impact on national NO_2 concentrations.

Vegetation should be relatively cheap to implement in a station but will require extensive maintenance to ensure that the plants stay in the best health for maximum deposition or air flow management to occur. Concerns exist regarding the longevity of vegetation in a station environment, with vegetation in enclosed stations likely to suffer from a lack of sunlight. In addition, urban environments can produce stressors which make it hard for plant species to survive long term, including the exposure to high concentrations of pollutants themselves (Haynes et al., 2019). However, as a mitigation option, it is likely to be a popular measure with members of the public as vegetation will improve station ambience.

4.4.3.2 Photocatalytic Surfaces

Photocatalytic surfaces act as a catalyst when exposed to ultraviolet light, with most photocatalytic paints or materials incorporating titanium dioxide (TiO_2) to break down NOx. The NOx is oxidated to surface-adsorbed nitrate which will then be washed off. The rate at which this reaction takes place has been found to be highly dependent on temperature, pressure, relative humidity and the level of the reagent NO_2 from various laboratory experiments (AQEG, 2016). Materials incorporating TiO_2 have been tested extensively, with the photocatalyst also being incorporated into a variety of devices. The French company Eurovia have produced paving slabs which have been installed in Kendal, Cumbria (Eminton, 2012). The company claims on their website that their NOx reduction technology, now being sold as either road-side barriers or pavements, reduce NOx by 30% at car level (Eurovia). The surfaces have also been used in a variety of art pieces intended to raise awareness of air pollution levels, such as the fabric poem hung in Sheffield made from a woven photocatalytic material. The creators of the poem claim that by using woven material rather than a flat coating increases the surface area in contact with the air by ten times (Holder, 2014).

A review by the Environmental Industries Commission (EIC), in collaboration with Imperial College London, covers twelve different trials where TiO_2 coatings have been used to reduce NO_2, showing mixed results (EIC, 2018). For example, a large-scale trial in Italy showed decreases in NO_2 in the surrounding air of 23% after photocatalytic paint was applied, but this trial required 6000 m^2 of surfaces to be coated with the photocatalytic paint, and incident sunlight levels are expected to have been considerably higher than those typically found in the UK. However, a 2007 trial in Camden, London, was inconclusive as to the effect the 135 m^2 of photocatalytic surface coating had on NOx levels. Such trials suggest that extensive and significant coating would be required for any kind of meaningful reduction to occur. Modelling by AQEG of a London-wide paint application in ADMS-Urban has suggested that NOx concentrations would be reduced by only 0.7% (AQEG, 2016). However, a model by Imperial College London produced for the EIC review suggested that the reductions would be in the range of 4.3% to 11.0% depending on whether the ground was also coated in the paint, with smaller reductions seen in the winter than in the summer. This model was simulating a typical London street canyon. Ultimately, the challenge will be in achieving a high enough amount of contact between the photocatalytic surface and the volume of air needing to be treated. With many devices that rely on surface contact, this can lead to a highly localised effect due to lack of circulation in enclosed environments such as stations, as discussed in Section 4.3.1. At this time, the exact impact of photocatalytic surfaces in any volume of space remains uncertain. A properly designed trial would be required to determine if this measure would have a meaningful impact.

Over time, the surfaces have been observed to become less effective catalysts. A study of photocatalytic asphalt pavement in Louisiana showed that activity reduced by up to 70% after an abrasion test was carried out (Hassan et al., 2013), suggesting that maintenance will be required to ensure effectiveness. In addition, the review by the EIC has provided a cost per application to range between 3.10 £/m^2 and 11.20 £/m^2 (EIC, 2018). Several studies have shown that unwanted biproducts can also be produced during the photocatalytic reaction, including ozone (Monge et al., 2010a) and nitrous acid (Monge et al., 2010b). Both of these pollutants are also associated with worse air quality.

4.4.3.3 Air Purification Devices: The CityTree

The CityTree is a commercially available device designed to filter fine dust, reducing the amount of PM in the air that passes through the device. Rather than using a replaceable filtration mechanism, the device is a three-metre high structure that uses a variety of species of moss to remove PM. In 2021, a CityTree has been placed in Newcastle station for a 12-week trial by LNER. Though the device is a green infrastructure solution, it differs from the passive filtering of urban vegetation discussed in Section 4.4.3.1 as it is an active filtering device, mechanically drawing in air from the surroundings to be filtered. As a result, the CityTree is likely to remove more PM from the air than an equivalently sized moss wall could achieve. The company claim that the CityTree will absorb up to 53% of the fine dust in its "immediate vicinity", however different studies have stated that the device removes 15±5, 23, or 26-64% of $PM_{2.5}$ (Nemitz et al., 2020). One independent study claims that the moss used in the CityTree has a bacterial film that absorbs inorganic compounds, with a retention rate of PM ten times higher than other plants at 20 g of PM per m^2 per year (Sänger and Splittgerber, 2016). As it is a vegetation-based design, the device will not reduce concentrations of NO_2. Due to issues with air circulation, the device is likely to have a highly localised impact on air quality, with the same volumes of air repeatedly being drawn through the device's filtration systems. As a result, the product's own website claims that the efficiency of the filtration is reduced from 53% to 33% when at a distance of 5 m. Each device filters 3,500 m^3 of air an hour, which is 27 times smaller than the approximate volume of air in Marylebone station. Therefore, there are concerns over whether such a device can process a large enough volume of air to make a meaningful difference to a station environment.

The CityTree costs €35,000 per unit, and due to relying on vegetation for filtration will likely require frequent maintenance to keep the moss healthy. Since the device utilises active filtration, it requires a 500 W power supply, though this may increase in later models as the company is currently considering adding more fans to draw a greater volume of air through the device. To be deployed at Newcastle station, extensive discussions and paperwork were required taking a total of 18 months to complete. Since the station trial began, issues with leaking of the device have occurred and concerns have been raised over the weight of the device and if it exceeds safe weight levels for the station floor.

4.4.3.4 Air Purification Devices: AirLab's AirBeams at Marylebone

In October 2018 Airlabs, in partnership with BNP Paribas, Chiltern Railways and JCDecaux, installed four bespoke air filtration devices called AirBeams inside cylindrical advertising casings on the concourse at Marylebone station. The AirBeams contain an electrostatic precipitator (ESP) filter designed to ionize PM in the air passing through it, with the now charged particle attracted to an oppositely charged plate inside the device. In addition, the AirBeams contain a carbon-based "Nano Filter" which removes gaseous pollutants such as NO_2. The device contains a fan to draw air into the device for filtration purposes. Each device can filter 2,000 m^3 of air an hour – in total, 8,000 m^3 of air will be filtered per hour by the devices, or 8% to 9% of the station's total air volume. The volume of air able to be processed is restricted by the size of the pre-existing advertising casings that the AirBeams had to be fitted inside, which also restricted the locations of the filtration devices within the station. AirLabs claims that the overall NO_2 removal efficiency of each device is 83%.

Computational fluid dynamics (CFD) modelling was carried out by AirLabs, which suggested that within a few metres of the devices the NO_2 concentrations were reduced by 50% and, towards the end of the concourse, NO_2 concentration reductions of 25-50% are anticipated (AirLabs, 2020). The company claims that this is due to the airflow within the station, which will aid the filtered air in circulating around the concourse. Measurements taken by Airlabs before and after the installation of the devices showed a 35% reduction in the concentrations of NO_2 at almost 2 m from the AirBeam, though no data was collected for distances further than 2 m. A year after the launch of the devices, further testing by AirLabs occurred, showing that the efficiency of the devices was approximately the same as it had been just after they were installed.

As the AirBeams were created as a bespoke product, they are not commercially available and therefore the cost per unit is unknown. Any device using an ESP or carbon-based filter will require them to be changed periodically to enable continuous efficient operation. This usually has to happen every 6 months, but since stations are highly polluted environments the required frequency is likely to be greater. The typical power of similarly sized devices is 200 – 600 W.

4.4.3.5 Air Purification Devices: IsCleanAir Air Pollution Abatement

IsCleanAir have developed a technology called Air Pollution Abatement (APA), a filtration system using chemical, physical, and mechanical processes designed to reduce concentrations of a variety of pollutants including NO_2 and PM. The difference with the APA technology from other purification devices is that it is filterless, with the air being purified passing through three stages, submerged in a tank of water. The first stage involves the liquid abatement of hydrocarbons in particulate form and heavy metals using a double step scrubber. For the second stage, electrolytic oxidation of light hydrocarbons takes place and the dissociation of NOx and SOx using a titanium oxide catalyst. Finally, the company claims that in the final stage, CO_2 is chemically transformed into bicarbonates by reaction with inorganic carbonates (Tripodi and Tripodi, 2009). There are concerns that titanium oxide catalysts may produce harmful biproducts such as ozone (Monge et al., 2010a) and nitrous oxide (Monge et al., 2010b), though IsCleanAir claim that the production of these substances is greatly reduced due to the process taking place in water. Since the system is filterless, the only biproduct is a fluid which has been certified as safe to be dischargeable into the sewage system of Italy by the Department of Industrial Engineering, Information and Economics in the Italian Government. The average water consumption of a unit is about 2-3 litres per day, with the full tank needing to be replaced every 4-6 months, however regular top ups of water are also required, typically every three weeks. Testing by the company has suggested that the systems require 14 hours of maintenance per 5,000 hours of operation.

The devices have been made to process various volumes of air depending on the environment, ranging between 300 m^3/h to 5,000 m^3/h, costing about £15,000 for a larger machine such as those that would be placed in a station. IsCleanAir originally designed the systems for use in industrial sites, but has since deployed the devices in a variety of places, such as airports, schools, and in Hahagana Train Station in Tel Aviv. The latter of these formed a trial taking place over a 4-week period between December 2019 and February 2020. Two APA Panel devices were installed at the station, each 1300 x 400 x 2100 mm in size and consuming 700 W of power. During the deployment, average pollutant abatement of 40% was measured for $PM_{2.5}$ and 50% for NOx within 25 m of the panels (Basat et al., 2020). These values include scaling and adjustments being made for temperature and humidity variation. The Haifa Bay Municipal Association for Environmental Protection independently verified these results, giving confidence in the results.

A Stage 2 trial at Hahagana Station was carried out between the 31st of December 2020 and the 17th of February 2021 where floats and sensors were installed in the APA panels to enable the volumes of water in the devices to be topped up automatically. Although this intervention greatly reduced the time spent on device maintenance, the efficiency of APA panels was also decreased due to a reduced amount of space for ambient air to enter the devices. With the Stage 2 interventions, average pollutant abatement was 25% for $PM_{2.5}$ and 45% for NOx (Basat et al., 2021). However, IsCleanAir are exploring how to build a system that can automatically fill without reducing efficiency.

Hahagana Station is a semi-enclosed environment, but similar APA panels have been deployed in large, enclosed spaces such as at Ciampino Airport in Rome in 2018 for a trial lasting 7 weeks. This trial measured pollutant abatement between 60 and 70%, as verified by an external company employed by the airport. However, it is not clear which pollutants these reductions were seen for, or how far away from the panels the measurements occurred.

4.4.3.6 Air Purification Devices: Other Filters

Although the CityTree, the AirBeams and the APA panels by IsCleanAir are the only devices known to have been specifically installed in a station environment, there are a variety of other air purification devices on the market. The vast majority of these, however, are designed for smaller enclosed environments such as for home, school, or medical centre use where the volumes of air to be filtered are significantly lower than in a rail station and therefore significant concerns exist over the scalability of the product to the station environment. In these lower air volume environments, heating, ventilation, and air conditioning (HVAC) systems often contain filters which are most often high-efficiency particulate air (HEPA) filters that can theoretically remove at least 99.97% of PM down to 0.3 µm in diameter from the air (US EPA, 2021). However, in practise the efficiency of removal is a lot less, especially for particles smaller than 10 µm in diameter which are the most damaging for human health (Royal College of Physicians, 2016). HEPA filters designed to fit into existing HVAC systems can cost between £40 and

£700 depending on size and efficiency. Air filtration systems designed purely as active filters are priced in the range of £200 to £3,000, however are designed for residential, school and hospital use therefore will not have a meaningful impact in a station environment. These filters also require frequent changing to ensure continuous efficiency, and do not have an impact on the concentrations of NO_2. Another small-scale device is the device called the AiroSafe, which are filtration devices that can be fitted to the seat of a bus, train, or underground railway carriage to provide filtered air to the passenger in that seat. It uses the same technology as the AirBeams, claiming to remove 95% of PM and NO_2, but on a much smaller scale as the system processes only 30 m^3 of air per hour. The AiroSafe filters last for approximately 4000 hours before needing to be changed, and the cost is likely to be similar to that of another commercially available product currently sold by the company, the AirBubbl, at £2,500.

In contrast, some devices are also inappropriate for station use due to their large size. The Solar-Assisted Large-Scale Cleaning System (SALSCS) in Xi'an, China is a 60 m tall solar-powered tower costing $2 million to build, designed to filter large amounts of PM from the air. When tested over a period of two weeks in winter when pollution is at its highest in Xi'an, an array of 10 monitors spanning a 10 km^2 area around SALSCS measured a reduction in $PM_{2.5}$ of 19%, filtering between 5 million to 8 million m^3 of air a day (Cyranoski, 2018). The size of this tower is significantly taller than would be practical in a station, however much smaller versions of this same concept are being proposed with heights ranging down to 10 m (Cao et al., 2018), although the size of this structure is also likely to pose significant installation challenges in a station. However, SALSCS purely focuses on filtering PM, which is not the primary pollutant of concern in stations. Equally, it is uncertain whether the devices, being solar powered, would be exposed to a high enough amount of sunlight to operate in an enclosed station.

Most other devices are designed to only reduce PM, with little to no impact on the levels of NO_2. For example, a collaboration between Studio Roosegaarde and ENS Clean Air has produced a device called the "Smog Free Tower", designed in the Netherlands. The 7 m tall device filters PM out of the air through electrostatic precipitation (Laxmipriya et al., 2018), consuming 1170 W of power to process 30,000 m^3 of air an hour. The company claim that the tower provides reductions in PM_{10} concentrations and $PM_{2.5}$ concentrations of 45% and 25%, respectively, within 20 m of the device in open air. Therefore, the reductions are likely to be higher in enclosed environments. Another device that processes a similar volume of air an hour, but is still in the early research phase, is a hybrid device using both soil and electrostatic precipitator (ESP) filters for PM reduction. Air is pulled through the device using a suction blower requiring a power of 6,250W, where the air is first filtered using 20 artificial soil filters before passing through two ESP filters in a tower of height 7 m. The creators of the device claim it to have a reduction efficiency in $PM_{2.5}$ of 78.5% (Elkamhawy and Jang, 2020), which is similar to many other available devices.

In 2018, SNCF, the French state-owned railway company, issued a call for solutions that could tackle air pollution in the Parisian Regional Express Network, a hybrid commuter rail and rapid transit system. The following year, Air Liquide was selected to experiment with six ESP filters deployed in underground railway stations to reduce PM concentrations at the Avenue Foch station for a trial that ran for six months. The company claim that these six filtration devices process 50,000 m^3 of air an hour, but there are no further details available on how efficient the systems were, or the outcomes of the trial. In 2020, SNCF also tested a liquid filtration system from Terrao, designed by the start-up Starklab. The device works by capturing particles by sucking air into the system and injecting it with water, though no further details on how the product works or its efficiency are publicly available.

As for reducing NOx concentrations, some success has been seen when using activated charcoal filters, which are used in the AirBeam technology deployed in Marylebone station. The benefit of activated charcoal filters is that they can usually be fitted to many ESP based filtration devices. In one study, combination HEPA and activated charcoal filters were placed in residential homes, and the median kitchen NO_2 concentrations decreased by 27% after 1 week of use, but this reduced to only 19% after three months (Paulin et al., 2014) which suggests that charcoal filters would need to be replaced regularly to ensure optimum filtration. Another study considered the use of charcoal filters in vehicle cabin air inlets to reduce exposure diesel exhaust fumes (Muala et al., 2014). Concentrations of NO_2 in the exposure chamber reduced by 75% when the activated charcoal filter was used. However, it is worth noting that the volume of air being filtered in a residential property and in a vehicle cabin are both several orders of magnitude smaller than the volume in an enclosed rail station. Although activated charcoal filters are cheap solutions, it is unlikely that the filtration system they were attached to could process large enough volumes of air to make a significant difference to NO_2 concentrations more than a couple of metres from the device.

4.5 Synthesis and Comparison

To provide an overview of the assessment outcomes a characteristics matrix is provided in Table 3 with a traffic light system:

- **Green (+)** - the measure is likely to have benefits in this area. The brighter the shade of green (and the more "+" symbols next to it), the larger the benefit is expected to be.
- **Yellow (0)** - the measure is likely to have little or no impact in this area. This categorisation is also shown by a "0".
- **Red (-)** - the measure is likely to pose challenges in this area. The darker the shade of red (and the more "-" symbols next to it), the larger the difficulties are expected to be.

Where these categorisations are not deemed appropriate, alternatives have been used. For the assessment criteria of **Applicability**, devices or measures already implemented in train stations have been assessed with a "Yes" and have been assessed with a "No" where they have not been. Where it is uncertain, a rating of "Maybe" has been given – for example, if the measure has definitely been implemented in an underground railway station but not necessarily in a train station. Similarly, for the criteria of **Independently Assessed**, a "Yes" indicates if the measure has been independently assessed specifically in a rail environment, and a "Maybe" has been given if the measure has been independently assessed but not in a rail environment.

Table 3 Characteristics matrix for off-engine mitigation options

Measure/device	Effectiveness of NO_2 exposure reduction	Effectiveness of PM exposure reduction	Scalability to Rail	Applicability	Commercial Feasibility	Long Term Sustainability	Operational Feasibility & Technical Practicability	Customer Perspective	Independently Assessed
Keeping exhaust fumes away from people									
Barriers	+/++	+/++	+	Maybe	-	0	--	-	Maybe
Boarding Areas	+	+	0/+	Yes	0	0	0/-/--	-	Yes
Air Curtains	+	+	--	Maybe	-	-	0	0/+	No
Changes to Train Flows	+++	+++	++	Yes	--	++	--	+	No
Mandatory Face Masks	0	+	--	Maybe	0	-	-	--	Maybe
Improved ventilation									
Natural Ventilation	++	++	+/++	Yes	-	-/0/+	-/--	0	Yes
Mechanical Extraction Systems	++	++	+	Yes	--	--	-/--	-	Yes
Off-engine mitigation									
Urban Vegetation	0	+	--	Maybe	0/-	+	-	++	Maybe
Photocatalytic Surfaces	+	0	--	Maybe	-	-	0	0	Maybe
The CityTree	0	+	--	Yes	-	-	-	0	Yes
AirLabs' AirBeams	+	+	--	Yes	-	-	-	0	No
IsCleanAir Air Pollution Abatement	+	+	-	Yes	-	-	-	0	Yes
HVAC/HEPA Filters	0	+	--	No	-	-	-	0	Maybe
AirLabs' Airosafe	+	+	--	Maybe	-	-	-	+	No
Solar-Assisted Large-Scale Cleaning System (SALSCS)	0	++	++	No	--	--	--	-	Maybe
Smog Free Tower	0	+	-	Maybe	-	-	-	0	No
Hybrid Soil Device	0	+	--	No	-	-	-	0	Maybe
Air Liquide Filtration Device	0	+	--	Yes	-	-	-	0	No
IP'Air Filtration Device	0	+	--	Yes	-	-	-	0	No
Activated Charcoal Filters	+	0	--	No	-	-	-	0	Maybe

4.6 Key messages and recommendations

There are clear challenges to meaningfully addressing air pollution using off-engine mitigation measures, particularly NO_2 emissions. Air pollutant reduction potential aside, installing many of these solutions in a station environment poses considerable complexity with ongoing maintenance, and its associated costs, a major barrier.

Although every effort has been made to carry out these assessments against independent evidence of each device, such studies are limited in number and scope. For example, most of the available literature on the real-world performance of filtration systems has been published by the instrument manufacturers. Therefore, assessments of the measures against the assessment criteria have a high level of uncertainty and thus could potentially lead to real world performance being worse than expected. Associated with this outcome would obviously be the public perception risk if a scheme resulted in lower pollutant reductions than anticipated or had other undesired consequences. For this purpose, it is recommended that the rail industry consider the following when examining a potential off-engine measure:

- Is it clear what technology is utilised in the device? Do the company's claims of the device's capabilities align with the known limitations of the technology?
- Which pollutants will the device reduce the concentrations of? NO_2 is a much greater issue in a station environment than PM.
- How long has the company been trading for? Is the technology backed up by patents? These two questions can indicate if a commercial product has longevity.
- Will a device process sufficient volumes of air to make a meaningful impact in a station environment?
- Are the company's claims backed up by an independent study?
- If pollutant concentration reductions are stated by the company, how were these conclusions made? Are the same measurements for the "before" and "after" device installation scenarios based on the same thing being measured e.g. are they both measuring average concentrations or peak concentrations?
- If measurements have been made, at what distance from the device were they taken? Were they right next to the device, or several meters away?
- If measurements have been made, how have ambient concentrations been considered? For example, if construction work is taking place close to where a device is being tested, this could be expected to potentially impact measured PM concentrations.

Changing train flows into enclosed stations would be the measure most likely to have the largest reduction in both PM and NO_2 concentrations in stations. However, the logistics to achieve this would be substantial, involving significant national cooperation between multiple train lines. Therefore, the measure most likely to be successful from a holistic perspective is improved ventilation. Mechanical extraction systems are costly, and present operational challenges and continued maintenance, as well as requiring the ongoing costs of the continuous energy supply required. On the other hand, natural ventilation would improve airflow and circulation, enabling dispersion of diesel exhaust fumes away from the station and thus reducing emissions exposure. The method with which this is achieved would be highly dependent on the existing infrastructure of any given station, as well as meteorological conditions locally such as wind speed and direction which must be taken into account before the measure is implemented. This is to prevent unintended and unexpected consequences from occurring, as changes in airflow can result in “dead spots” where pollutant concentrations can build up to levels above safe limits. Any ventilation measure should be suitable for the average wind direction, usually from the southwest, but also function as intended when the prevailing wind is coming from other directions too.

Ultimately, off-engine measures are unlikely to result in the same pollutant concentration reductions that could be achieved through the implementation of fleetwide on-engine measures, or improved electrification of the railways nationally.

5 References

Abbasi, S. A., Khalil, A. B. & Arslan, M., 2020. Extensive use of face masks during COVID-19 pandemic: (micro-)plastic pollution and potential health concerns in the Arabian Peninsula. *Saudi Journal of Biological Sciences*, 27 (12), pp. 3181-3186

Abhijith, K. et al., 2017. Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments – A review. *Atmospheric Environment*, 162, pp. 71-86.

AirLabs, 2020. AirLabs Case Study: Reducing air pollution exposure inside Marylebone Station.

Anderson, J. O., Thundiyil, J. G. & Stolbach, A., 2012. Clearing the Air: A Review of the Effects of Particulate Matter Air Pollution on Human Health. *Journal of Medical Toxicology*, 8(2), pp. 166-175.

AQEG, 2016. Paints and Surfaces for the Removal of Nitrogen Oxides. Report of the Air Quality Expert Group prepared for Department for Environment, Food and Rural Affairs, Scottish Government; Welsh Government; and Department of the Environment in Northern Ireland 2016. https://uk-air.defra.gov.uk/assets/documents/reports/cat11/1604130958_PB14425_Paints_and_Surfaces_for_the_Removal_of_Nitrogen_Oxides.pdf

AQEG, 2018. Impacts of Vegetation on Urban Air Pollution. Report of the Air Quality Expert Group prepared for Department for Environment, Food and Rural Affairs, Scottish Government; Welsh Government; and Department of the Environment in Northern Ireland 2018. https://uk-air.defra.gov.uk/assets/documents/reports/cat09/1807251306_180509_Effects_of_vegetation_on_urban_air_pollution_v12_final.pdf

Baldauf, R. et al., 2008. Impacts of Noise Barriers on Near-Road Air Quality. *Atmospheric Environment*, 42 (32), pp. 7502-7507.

Baldauf, R. W. et al., 2016. Influence of solid noise barriers on near-road and on-road air quality. *Atmospheric Environment*, 129, pp. 265-276.

Basat, R. B., Bitton, S., Avveduto, A. & Tripodi, P., 2020. Technical Report Tel'Aviv Hahagana Train Station. Report prepared for Is Clean Air Italia S.r.l.

Basat, R. B., Bitton, S., Avveduto, A. & Tripodi, P., 2021. Technical Progress Report Tel'Aviv Hahagana Train Station. Report prepared for Is Clean Air Italia S.r.l.

Berner International Corp., Industrial Parts Manufacturer Installs Air Door for Energy Efficiency and Gets IAQ Surprise. [Online] Available at: https://berner.com/case-studies/coleman-tools/ [Accessed 4 November 2021].

Building Services & Environmental Engineer, 2013. Air Curtains for Air Quality. [Online] Available at: https://www.bsee.co.uk/air-curtains-for-air-quality/ [Accessed 4 November 2021].

Cao, Q. et al., 2018. Urban-scale SALSCS, Part I: Experimental Evaluation and Numerical Modeling of a Demonstration Unit. *Aerosol and Air Quality Research*, 18 (11), pp. 2865-2878.

Carlsten, C., Salvi, S., Wong, G. W. & Chung, K. F., 2020. Personal strategies to minimise effects of air pollution on respiratory health: advice for providers, patients and the public. *European Respiratory Journal*, 55 (6), elocation-ID: 1902056.

Cleaner Construction for London, 2020. Non-Road Mobile Machinery (NRMM) Practical Guide V.4.

Clegg, M. et al., 2022. Intervention of an Upgraded Ventilation System and Effects of the COVID-19 Lockdown on Air Quality at Birmingham New Street Railway Station. *International Journal of Environmental Research and Public Health*, 19, article no: 575.

Comunian, S., Dongo, D., Milani, C. & Palestini, P., 2020. Air Pollution and COVID-19: The Role of Particulate Matter in the Spread and Increase of COVID-19's Morbidity and Mortality. *International Journal of Environmental Research and Public Health*, 17 (12), pp. 4487.

Cyranoski, D., 2018. China tests giant air cleaner to combat smog. *Nature*. [Online] 8th March 2018; 555 (7695), pp. 152-153. Available at: https://www.nature.com/articles/d41586-018-02704-9 [Accessed 22 November 2021].

Department for Transport, 2021. Guidance overview: TAG data book. [Online] Available at: https://www.gov.uk/government/publications/tag-data-book [Accessed 9 November 2021].

Dharmaraj, S. et al., 2021. The COVID-19 pandemic face mask waste: A blooming threat to the marine environment. *Chemosphere*, 272, article no. 129601.

EIC (Environmental Industries Commission), 2018. Towards Purer Air: A review of the latest evidence of the effectiveness of photocatalytic materials and treatments in tackling local air pollution.

Elkamhawy, A. & Jang, C.-M., 2020. Performance Evaluation of Hybrid Air Purification System with Vegetation Soil and Electrostatic Precipitator Filters. *Sustainability*, 12(13), article no. 5428.

Eminton, S., 2012. Kendal street to be fitted with 'anti-pollution' paving. [Online] Available at: https://airqualitynews.com/2012/04/20/kendal-street-to-be-fitted-with-anti-pollution-paving/ [Accessed 19 November 2021].

Eurovia, NOxer. [Online] Available at: https://www.eurovia.fr/nos-solutions/par-gammes/environnement/noxer [Accessed 19 November 2021].

Gil-Lopez, T., Gálvez, M. A., Castejon-Navas, J. & Gomez-Garcia, V., 2013. Experimental analysis of energy savings and hygrothermal conditions improvement by means of air curtains in stores with intensive pedestrian traffic. *Energy and Buildings*, 67, pp. 608-615.

Greater London Authority, 2019. Using Green Infrastructure to Protect People from Air Pollution. Published by the Greater London Authority, London.

Hartig, T., Mitchell, R., de Vries, S. & Frumkin, H., 2014. Nature and Health. *Annual Review of Public Health*, 35, pp. 207-228.

Hassan, M. et al., 2013. Sustainable Photocatalytic Asphalt Pavements for Mitigation of Nitrogen Oxide and Sulfur Dioxide Vehicle Emissions. *Journal for Materials in Civil Engineering*, 25, pp. 365-371.

Haynes, A. et al., 2019. Roadside Moss Turfs in South East Australia Capture More Particulate Matter Along an Urban Gradient than a Common Native Tree Species. *Atmosphere*, 10 (4), pp. 224.

Hayes, D., 2021. The Clean Vehicle Retrofit Technology Guide. Report prepared by Zemo Partnerships, London.

Health and Safety Executive, 2018. EH40/2005 Workplace Exposure Limits: Containing the List of Workplace Exposure Limits for Use with the Control of Substances Hazardous to Health Regulations 2002 (as amended).

Hickman, A. et al., 2018. Evaluation of air quality at the Birmingham New Street Railway Station. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 232 (6), pp. 1864-1878.

Highways England, 2019. Summary of research projects to improve air quality on or close to the strategic road network.

HMSO, 1963. Offices, Shops and Railway Premises Act. (c. 41).

Holder, M., 2014. Giant Simon Armitage poem used to cut NO_2 pollution. *Air Quality News*. [Online] Available at: https://airqualitynews.com/2014/05/14/giant-simon-armitage-poem-used-to-cut-no2-pollution/ [Accessed 19 November 2021].

Huertas, J. I., Aguirre, J. E., Lopez Meija, O. D. & Lopez, C. H., 2021. Design of Road-Side Barriers to Mitigate Air Pollution near Roads. *Applied Sciences*, 11 (5), article no: 2391.

IAQM, 2019. Mitigation Measures: Ambient Pollution Removal Techniques. Report of the Institute of Air Quality Management. https://iaqm.co.uk/text/position_statements/ambient_pollution_removal_techniques.pdf

Jones, L. et al., 2017. Developing Estimates for the Valuation of Air Pollution Removal in Ecosystem Accounts. Report of the Office for National Statistics.

Kumar, P., Omidvarborna, H., Barwise, Y. & Tiwari, A., 2020. Mitigating Exposure to Traffic Pollution In and Around Schools. Report of the Global Centre for Clean Air Research, University of Surrey.

Lapworth, A. & McGregor, J., 2008. Seasonal variation of the prevailing wind direction in Britain. *Weather*, 63 (12), pp. 365-368.

Laxmipriya, S., AjayKumar, A., Aravinthan, S. & Arunachalam, N., 2018. Reduction of Air Pollution Using Smog-Free-Tower A Review Paper. *International Research Journal in Advanced Engineering and Technology*, 4(2), pp. 3251-3255.

Milford, I., Asebo, S. J. & Strommer, K., 2012. Value for Money in Road Traffic Noise Abatement. *Procedia - Social and Behavioral Sciences*, 48, pp. 1366-1374.

Monge, M. E., D'Anna, B. & George, C., 2010b. Nitrogen dioxide removal and nitrous acid formation on titanium oxide surfaces--an air quality remediation process? *Physical Chemistry Chemical Physics*, 12(31), pp. 8991-8998.

Monge, M. E. et al., 2010a. Ozone formation from illuminated titanium dioxide surfaces. *Journal of American Chemical Society*, 132(24), pp. 8234-8235.

Muala, A. et al., 2014. Assessment of the capacity of vehicle cabin air inlet filters to reduce diesel exhaust-induced symptoms in human volunteers. *Environmental Health*, 13, article no. 16.

Nemitz, E. et al., 2020. Potential and Limitation of Air Pollution Mitigation by Vegetation and Uncertainties of Deposition-Based Evaluations. *Philosophical Transactions of The Royal Society A Mathematical Physical and Engineering Sciences*, 378 (2183), article no: 20190320.

Nor, N. S. M. et al., 2021. Particulate matter ($PM_{2.5}$) as a potential SARS-CoV-2 carrier. *Nature Scientific Reports*, 11, article no: 2508.

Office of Rail and Road, 2020. Rail Infrastructure and Assets 2019-20.

Paulin, L. et al., 2014. Home Interventions are Effective at Decreasing Indoor Nitrogen Dioxide Concentrations. *Indoor Air*, 24 (4), pp. 416-424.

Rail Safety and Standards Board, 2018. GIRT7020 GB Requirements for Platform Height, Platform Offset and Platform Width.

Rail Safety and Standards Board, 2020. Air Quality Strategic Framework.

Rail Safety and Standards Board, 2021. CLEAR: Analysis of Air Quality On Board Trains (T1188).

Royal College of Physicians, 2016. Every Breath We Take: The Lifelong Impact of Air Pollution. *Clinical Medicine (London)*, 17 (1), pp. 8-12.

SAGE Environment and Modelling Group, 2020. Simple summary of ventilation actions to mitigate the risk of COVID-19.

Sá, J. P. et al., 2017. Evaluation of Low-Cost Mitigation Measures Implemented to Improve Air Quality in Nursery and Primary Schools. *International Journal of Environmental Research and Public Health*, 14 (6), article no: 585.

Sänger, P. & Splittgerber, V., 2016. The CityTree: A Vertical Plant Filter for Enhanced Temperature Management. In book: *Innovation in Climate Change Adaptation*. Leal, W. ed. Springer Cham, pp. 75-85.

Son, Y.-S. et al., 2013. The Effect of Platform Screen Doors on PM_{10} Levels in a Subway Station and a Trial to Reduce PM_{10} in Tunnels. *Asian Journal of Atmospheric Environment*, 7(1), pp. 38-47.

Staten Island Rapid Transit Ry. Co. v. Public Service Commission of State of New York, 16 F.2d 313 (1926). District Court, New York.

The Mayor's School Air Quality Audit Programme, 2018. Toolkit of Measures to Improve Air Quality at Schools. Report by Greater London Authority.

Thornes, J. et al., 2021. Proposed interventions to reduce noxious air pollution at Birmingham New Street station. *Proceedings of the Institution of Civil Engineers - Transport*, 174, pp. 1-6.

Tomson, M. et al., 2021. Green infrastructure for air quality improvement in street canyons. *Environment International*, 146, article no. 106288.

Transport Scotland, 2021. Data held on the Bus Emissions Abatement Retrofit programme: Freedom of Information/EIR release under the Environmental Information (Scotland) Regulations 2004. [Online]. Available at: https://www.gov.scot/publications/foi-202100200788/

Tripodi, P. & Tripodi, M., 2009. *System for Air Pollution Abatement*. Italy, Patent No. EP2119490.

UNECE, 2018. Regulation No 132 of the Economic Commission for Europe of the United Nations: Uniform provisions concerning the approval of Retrofit Emission Control devices (REC) for heavy duty vehicles, agricultural and forestry tractors and non-road mobile machinery equipped with compression ignition engines [2018/630]. *Official Journal of the European Union*, L 109, pp. 100-154.

US EPA, 2021. What is a HEPA filter?. [Online] Available at: https://www.epa.gov/indoor-air-quality-iaq/what-hepa-filter-1 [Accessed 23 November 2021].

Viecco, M. et al., 2021. Green roofs and green walls layouts for improved urban air quality by mitigating particulate matter. *Building and Environment*, 204, article no. 108120.

Wen, Y. et al., 2020. Environmental and Health Effects of Ventilation in Subway Stations: A Literature Review. *International Journal of Environmental Research and Public Health*, 17 (3), article no. 1084.