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CLEAR: Fleet-Wide Assessment of Rail Emissions Factors

RESEARCH AND
DEVELOPMENT

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Executive Summary

This report is aimed at environmental, engineering and finance staff in organisations throughout the GB rail industry. It is intended to help stakeholders understand the how rail emissions are generated and how they have been previously estimated. A more granular approach to estimating real world emissions is then presented that enables evaluation of the impact of rail emissions on local air quality, and of the effectiveness of different approaches to reducing rail emissions.

At the national level, the rail network's contribution to total annual UK air pollutant emissions is small; for example, in 2018 it was estimated to account for approximately 2% of nitrogen oxide (NO_x) emissions. Emissions are also expected to decline due to additional electrification and the use of bi-mode trains increases. However, although the contribution of rail emissions at the national level can be small, the impact at a local level can be significant. This has been shown in results from air quality monitoring undertaken at Birmingham New Street, Edinburgh Waverley and London Kings Cross stations, where high measured NO_x concentrations were recorded.

Currently the emission factors utilised in the UK's annual National Atmospheric Emissions Inventory (NAEI) for the rail sector are more limited than that used for other sources. Just one emission factor is available per generic train class in grams per kilometre. Therefore, these factors do not take account of sub-classes, and of variations in drive cycles, loadings and gradients.

In addition to the need to improve estimates of emissions from the rail sector nationally, improved emission factors are also required to better understand air quality impacts in local areas, such as stations and urban rail freight yards. This will provide the rail industry with the data necessary to respond to any future regulatory requirements and provide policy makers with robust data on which they can base strategy decisions.

The main objectives of this project were to:

- review current rail emission factors for the current and projected GB passenger and freight rolling stock fleet
- provide technical justification for new emission factors as a function of notch (the engine operating mode)
- compile relevant data and develop new emission factors
- identify how new emission factors can be used to guide future improvements in rail emissions
- evaluate the sensitivity of NO_x, PM and CO_2 emissions to various operational factors
- assess the relative importance of non-exhaust (abrasion) emissions from rail and whether additional PM emission factors may be required for these emissions
- make recommendations for future work.

Rail emissions testing and certification in Europe has lagged behind that undertaken in the United States, which first regulated this sector in 1973. In Europe, initially regulations (which were voluntary for the UK) were developed by the Union International des Chemins-de-Fer (UIC), starting with UIC standards 1 and 2, which came into effect in 1993 and 2003, respectively. These have since been superseded by the European Commission's Non-road Mobile Machinery Directive, which provides emission limits (in grams/kWh over a given drive cycle) for railcars and locomotives under increasingly stringent standards, known as Stage IIIA, Stage IIIB and Stage V.

The given drive cycle for an emission standard will include a specific amount of time at idle, at full throttle at maximum engine speed and some intermediate conditions. Therefore, the weighting and test points may not reflect real world use and future reductions in the emission limit value does not necessarily mean that emissions will be uniformly reduced across all engine operating conditions.

Therefore, the use of emission limit values to directly estimate emissions from the rail sector are not recommended. Instead, it is recommended that emission factors by notch are made available. By considering emissions as a function of useful energy delivered in different engine operating mode points (notches), total emissions for specific routes can be calculated according to the operation of the train by using on-train monitoring recorder (OTMR) and loading data; this is important since emissions of many pollutants are not linearly related with engine power output or fuel consumption. Emission factors by notch (in units of g/kWh) can serve as a key foundation on which to build emission factors in other units. For instance, it is possible to derive emission factors in terms of g/km by combining g/kWh emission factors with OTMR data on the distance travelled while the engine is in a certain notch. A key benefit of providing emission factors by notch, is that they can be used at a range of scales and provide more accurate national emission totals as well as evaluating local impacts, particularly of idling trains. These factors will enable evaluation of the rail industry's ability to comply with future emissions standards or restrictions relating to local air quality, while at the same time being, overall, a low-cost option with a broadly applicable approach.

For diesel electrical transmission, engine data (power curves, notch setting, fuel consumption curves) as well as engine emissions testing data at various power outputs, and drive cycle or OTMR data are required to develop emission factors by notch. All GB freight trains have electrical transmission and therefore fall in this category. While the notch system is well understood for older diesel electric trains and locomotives, more modern trains and locomotives have an electrical transmission described as 'continuously variable' rather than having fixed power (and brake) notches. However, there is more often a number of fixed notches available that the engine runs at.

Developing emission factors by notch for diesel hydraulic transmission is more complicated than that for diesel electric and the following additional information is required: gearbox data, final drive gearbox ratio and information on the wheel diameter. The recent trend has been for new regional/local DMUs to be fitted with mechanical transmission to improve fuel efficiency and performance on services with lots of stops, where far more time is spent at lower speeds. OTMR data from these units can be combined with detailed technical data from the manufacturer to enable better emission factors to be obtained. With mechanical transmission, the data and understanding will have good transferability between routes.

In summary, emission factors by notch have been developed for these train classes:

- Sprinters (Classes 150, 153, 155, 156)
- Express Sprinters (Classes 158, 159)
- Network Turbos (Classes 165, 166)
- Turbostars - Hydraulic transmission (Classes 168, 170, 171)
- Turbostars - Mechanical transmission (Class 172)
- Civity (Class 195)
- Voyager/Meridians (Classes 220, 221, 222)
- Flirt (Class 755)
- IET (Classes 800, 802)
- HST (Class 43)
- Classes 57, 59, 60, 66 67, 68.

These are the most common locomotive and rolling stock types covering ~85% of current passenger diesel mileage and ~95% of freight diesel mileage in 2018.

At present, the UK NAEI rail emission estimates are based on combustion emissions only with no abrasion estimates. Given the increasing interest in non-combustion emissions from the road transport sector due to its increasing contribution to total road transport emissions as exhaust emissions decline, a brief assessment of the information available on non-combustion emissions from the rail sector has been collated.

Rail transportation has higher efficiency, lower rolling resistance and lower material wear rates than road transport, resulting in a comparatively lower material volume produced as particulates. However, there is a lack of high-quality rail abrasion particle studies, with many being of narrow focus or having significant technical limitations. Many review papers of rail emissions focus on particular areas, for example focusing just on rail/wheel wear and braking but ignoring electrical contact/conductor wear, and do not attempt to quantify what total rail non-combustion emissions might be. Non-combustion related particulates are typically one to two orders of magnitude smaller than combustion particulates.

Key findings from the project are:

- Because of assumed proportionality to fuel usage and assumption of a single unrealistic drive cycle, previous emission factors for air quality pollutants have overstated emissions at the journey level and consequently led to high national emissions totals. Furthermore, the previous emission factors, which are based on distance travelled, do not accurately represent emissions at low speed and idle.
- For all locomotive and train classes, emissions of air quality pollutants (specifically NO_X and PM) do not directly correlate with power output and thus with fuel consumption (and so CO_2 emissions).
- Emissions arising when trains are at idle are significant. On a g/kWh basis, NO_X emissions are significantly higher in idle versus other notches for all engine types. A similar but less pronounced trend is present for PM where idle is also always higher versus other notches.
- A high proportion of a train’s drive cycle is spent in idle. From analysing OTMR data, this was found to be always over 50%, and usually over 60% in most cases for all types of passenger trains and freight locomotives. It is therefore important to consider the emissions arising during this element of the journey. Solutions that reduce train idling are likely to have a significant impact on local air quality issues.
- Emissions by notch combined with an understanding of the typical drive cycle for each locomotive or train class can be used to derive improved emission factors in units of g/km. OTMR data is needed to fully understand the drive cycle to correlate the engine operation and emissions produced with distance travelled. For example, using a revised g/km emission factor for long formation HSTs, the annual NO_X emissions for 2016 would be lower by 1,755 tonnes (a 7% reduction in total NO_X emissions from rail). The impact is particularly marked for PM since in recent years HSTs have accounted for 49% of total PM emissions from rail. The annual PM emissions for 2016 with the revised HST particulate matter emission factor would be lower by 301 tonnes (a 32% reduction in total PM emissions from rail).
- When combined with detailed OTMR data for specific routes, emission factors by notch can be used to demonstrate the sensitivity of emissions of NO_x, PM and CO_2 to various operational factors (such as the number of stops and variations in loading) for both passenger and freight trains. In addition, more accurate g/tonne-km emission factors for specific freight trips can be derived that can enable more meaningful intermodal comparisons.

- Abbreviations

AQP	Air quality pollutant
AAR	Association of American Railroads
AESS	Automatic engine stop/start
APEG	Airborne Particles Expert Group
BSFC	Brake specific fuel consumption
BS	British Standard
BR	British Rail
C-DAS	Connected Driver Advisory System
CAZ	Clean Air Zone
CH_4	Methane
CHP	Combined heat and power
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CAZ	Clean Air Zone
CCC	Committee on Climate Change
CLEAR	Clean Air Research Programme
Defra	Department for Environment, Food and Rural Affairs
DfT	Department for Transport
DMU	Diesel multiple unit
DOC	Diesel Oxidation Catalyst
DPF	Diesel particulate filter
EC	European Commission
ECML	East Coast Mainline
EPA	Environmental Protection Agency
EU	European Union
ECU	Engine control unit
FOC	Freight operating company
FTA	Freight Transport Association
GHG	Greenhouse gas
GWP	Global warming potential
GWML	Great Western Mainline
HST	High Speed Train
IET	Intercity Express Train
IGBT	Insulated-gate bipolar transistor

ISO	International Standards Organisation
LAEI	London Atmospheric Emissions Inventory
LRC	London Research Consortium
MML	Midland Mainline
N_2O	Nitrous oxide
NAEI	National Atmospheric Emissions Inventory
NBfL	New Bus for London
NMVOC	Non-methane volatile organic compounds
NO_X	Nitrogen oxides
OTMR	On-train monitoring recorder
NRMM	Non-road mobile machinery
PAH	Polycyclic aromatic hydrocarbons
PM	Particulate matter
$PM_{0.1}$	Particulate matter with an aerodynamic diameter of ≤0.1 µm
$PM_{1.0}$	Particulate matter with an aerodynamic diameter of ≤1.0 µm
$PM_{2.5}$	Particulate matter with an aerodynamic diameter of ≤2.5 µm
PM_{10}	Particulate matter with an aerodynamic diameter of ≤10 µm
PRM	Persons of reduced mobility
PEMS	Portable emissions measurement system
REM	Rail Emissions Model
ROSCO	Rolling stock operating company
RSSB	Rail Safety and Standards Board
SCR	Selective catalytic reduction
SO_2	Sulphur dioxide
TfW	Transport for Wales
TOC	Train operating company
TOPS	Total Operations Processing System
TRUST	Train Running Under System TOPS
UIC	International Union of Railways
ULSD	Ultra-low sulphur diesel

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- Hitachi
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- Hull Trains
- MTU
- Network Rail
- Northern
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1 Introduction

RSSB has established an Air Quality Steering Group comprising members from across the rail industry and is in the process of developing a Rail Air Quality Strategy. The strategy will be launched in Spring 2020 and will be underpinned by the Clean Air Research Programme (CLEAR). CLEAR incorporates robust research to measure air quality on the rail network and gain a better understanding of rail's contribution to local pollution levels. As well as informing the development of the Rail Air Quality Strategy, this research will also support the industry in establishing a 'baseline' from which improvement measures can be implemented and evaluated against.

Emission factors are a key tool for estimating emissions of pollutants but those currently used to estimate GB rail emissions are out of date and provide a poor representation of how emissions vary according to engine operating condition. This particular report covers the main findings of the RSSB T1187 project, *CLEAR: Fleet wide assessment of rail emission factors*, one of several CLEAR projects. An associated report[1] covers analysis of the impacts of operational requirements on emissions.

1.1 Project objectives

The objectives of this project were to:

- review current rail emission factors for the current and projected GB passenger and freight rolling stock fleet
- provide technical justification for new emission factors as a function of notch (the engine operating mode)
- compile relevant data and develop new emission factors
- identify how new emission factors can be used to guide future improvements in rail emissions
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- assess the relative importance of non-exhaust (abrasion) emissions from rail and whether additional PM emission factors may be required for these emissions
- make recommendations for future work.

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[1] Mansell, G., R. Brook, N. Grennan-Heaven and M. Gibbs (2020). *T1187 CLEAR: Fleet wide assessment of rail emissions factors – Emission scenarios report*. RSSB.

1.2 Project context

1.2.1 Rail emissions and air quality

Air quality is recognised as a significant public health issue, with transport a major contributor to emissions of air quality pollutants. In previous versions of the UK National Atmospheric Emissions Inventory (NAEI), NO_X emissions from both passenger and freight diesel trains were estimated to account for 4% of the UK's total NO_X emissions. However, recent revisions to the NO_X emission factors for the Class 66 locomotive and many diesel multiple units (DMUs) have reduced this proportion to 2% of national NO_X emissions. Furthermore, this proportion is expected to reduce further due to new electrification schemes and the increased use of bi-mode trains. Nevertheless, while at the national level rail emissions may be relatively minor, these can be significant locally.

At the local level, responsibility for air quality has been devolved to local authorities and over 600 Air Quality Management Areas (AQMA) have been declared across the UK. Clean Air Zones (CAZ) are likely to be the primary tool through which local air quality issues are tackled in the worst performing areas. Implementation of CAZs is currently underway or being studied in many cities. London introduced the Ultra-Low Emissions Zone (ULEZ) in April 2019 which has bought about significant improvements in air quality and dramatically reduced exposure to poor air quality for those living within the zone. As road emissions reduce, driven by regulation and policy advances, the rail industry will need to ensure it makes similar improvements. RSSB is currently working with rail industry stakeholders to develop a Rail Air Quality Strategy, for which this study will provide input.

Of particular importance is that emissions of air pollutants are not simply linearly related to speed and distance travelled because of the complexities of the combustion process. Thus, a simple consideration of fuel consumption, while useful for addressing decarbonisation, will not yield a complete picture of when and how air quality pollutants are produced. For example, with the formation of NO_X, in diesel engines virtually all the nitrogen and oxygen are sourced from the air (thermal NO_X) rather than any contaminants in the fuel (fuel NO_X) and the quantities formed are a result of how combustion occurs.

More specifically, NO_X production is effectively maximised under engine idle conditions. Hence comparatively more NO_X is produced at idle than at other (higher) engine power conditions per unit of power output or fuel consumption.

Air quality issues (high concentrations that are above legal limits) can develop where dispersion of emissions is limited. Situations where high emissions and high local concentrations of air pollutants can arise include idling and accelerating at low speed and where air flow is limited such as in covered station environments. Consequently, it is necessary to have a robust and detailed understanding of how, when and where emissions of air pollutants are generated by rail diesel engines and to therefore understand the exact impact of the proposed mitigation measures. Disregarding such a detailed approach may lead to ineffective measures to address air quality issues.

1.2.2 Rail greenhouse gas (GHG) emissions

In addition to air quality issues, the rail industry must also address the need to reduce emissions of GHGs such as carbon dioxide (CO_2) that are driving climate change. The UK Committee on Climate Change (CCC) has set targets for 2050 to reduce carbon emissions by at least 80% (from 1990 levels) overall[2], with a 43% reduction achieved by 2018[3]. Land-based transport has recently been set the target to reduce emissions by 100% albeit with a limited amount of off-setting allowed. This is challenging, in different ways, for the passenger and freight rail sectors. In April 2018, the then Rail Minister Jo Johnson set the target to remove diesel-only traction from GB rail network by 2040 (multi-source powered rolling stock would still be allowed with diesel as one of the sources). Thus, the payback period on any investment in (either new or upgraded) diesel-only stock is limited to 20 years before such rolling stock would have to be withdrawn.

The industry's response to the minister's challenge, developed by the Rail Industry Decarbonisation Taskforce and RSSB, includes measures (such as electrification and use of hydrogen) which will also lead to a reduction in the emission of local air pollutants. However, any efforts to reduce air pollutants from GB rail must not negatively impact the decarbonisation efforts and vice versa. The rail decarbonisation and air quality strategies will be developed in parallel and in consideration of each other.

In this project emission factors by notch were developed for NO_X, PM, CO_2 and fuel consumption. This will allow the RSSB decarbonisation and air quality work streams to successfully interact and evaluate the impacts on production of other pollutants when measures to address one particular pollutant are considered.

1.3 Emission factors

Where emissions data is not directly available from measurements, emission estimates are usually calculated by applying an average emission factor to an appropriate activity statistic. That is:

$$\text{Emissions} = \text{Emission Factor} \times \text{Activity}$$

Emission factors are generally derived from pollutant-specific emission measurements based on a number of sources representative of a sector. They can vary significantly in quality, complexity and accuracy. Emission factors can be expressed in different

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[2] https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

[3] https://www.theccc.org.uk/publication/reducing-uk-emissions-2019-progress-report-to-parliament/

measurement units, which can have a significant effect on their ease of use for detailed analysis or comparisons.

The **Activity** statistic can be provided at different levels of granularity. For simplicity, the activity statistic could be an estimate of the total activity (e.g. total mileage or km of a particular type of rail service), or a more complex approach to rail drive cycles could be used. In the latter case, the amount of time spent in idle, full throttle or intermediate engine settings is accounted for to provide an itemised understanding of different types of activity. These activity statistics would then be combined with appropriate emission factors, so that an overall emission for a journey or proportion of journey is calculated.

Current rail emission factors (such as those utilised in the UK National Atmospheric Emissions Inventory, NAEI) are based on a single fixed drive cycle (a set certain proportion of time in idle, at full speed, etc is assumed) for each locomotive or train class and this is combined with an estimate of total activity to derive an emission estimate. While a fixed drive cycle provides further information than a simple estimate of total activity, a more sophisticated treatment which looks at the drive cycle in detail must ensure that the emission factors and the specific activity align, that they can be related to each other.

1.3.1 Potential for improvement

The NAEI rail emission factors used to estimate national level emissions for the UK and are of limited use in detailed (regional, local or multimodal) studies because of:

- the calculation methodology (the measurement units are in grams of pollutant per train or vehicle kilometre travelled and no account is taken of different drive cycles)
- the data quality and assumptions used
- some use of conservative or proxy values
- continued use of certain data that is no longer applicable
- no relevant data for new rolling stock.

Each of these issues is discussed further in Section 4. In summary, the NAEI rail emission factors are more limited compared to other emission sources, e.g. road vehicles in urban areas (where the focus on air quality is likely to be the most intense). More robust factors are required for policy or business investment decision making, particularly since air quality concerns have risen up the public agenda. Improvements in emission factors for the rail sector are therefore required reflecting:

- That data quality and emissions calculation methods for other transport modes have improved and the corresponding rail data and methods need to be updated to ensure more robust comparisons.
- That accurate estimates of air pollutant emissions such as nitrogen oxides (NO_X) and particulate matter (PM) require detailed calculations. This is in comparison to estimating carbon dioxide (CO_2) emissions or fuel consumption which has often been

the historic focus of previous emissions and sustainability studies[4]. The production of air pollutants is less directly related to energy consumption and is more dependent on the conditions in which the fuel is burnt.

- The potential for the current calculation methodology to over-estimate emissions in some cases, due to assumptions surrounding drive cycles. For example, currently no account is taken of the distance covered while the engine is running in idle, e.g. coasting. While this is less of an issue for estimates of CO_2 emissions (because their impact is not local and total fuel consumption hence CO_2 emission estimates are known) it is important for estimates of air pollutant emissions.

In addition to the need to improve estimates of total emissions from the rail sector, so as to better understand the sector's contribution to national totals, improved emission factors are also required to better understand air quality impacts in local areas, such as major stations and urban rail freight yards. It is, therefore, important that the emission factors are improved for as many diesel locomotives and diesel multiple units (DMUs) as possible so that a more accurate reflection of rail's greenhouse gas (GHG) and air quality impact is provided. This will provide the rail industry with the data necessary to respond to any future regulatory requirements and provide policy makers with robust data on which they can base strategy decisions.

By considering emissions as a function of useful energy delivered in different engine operating mode points (notches)[5], total emissions can be calculated according to the operation of the train; this is important since emissions of many pollutants are not linearly related with engine power output or fuel consumption. Emission factors by notch can be used at a range of scales. They can provide more accurate national or high-level emission totals as well as evaluating local impacts, particularly of idling trains. This issue has been recently identified as of key importance by the University of Birmingham's work at Birmingham New Street[6] and RSSB's T1122 project[7], which assessed air quality at Edinburgh Waverly and London Kings Cross. Furthermore, by benchmarking possible changes against an accurate baseline of current emissions, more robust identification of improvements can be made, thus enabling more effective evidence-based policy decisions based on real world data rather than high level calculated estimates using proxy values.

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[4] Lindgreen, E.B.G., and S.C. Sorenson (2005). *Simulation of energy consumption and emissions from rail traffic*. Technical University of Denmark. Department of Mechanical Engineering, Report MEK-ET-2005-04.

[5] Power or throttle 'notch' in rail terminology is used to describe a fixed power output setting of the engine. Most GB diesel rail vehicles have fixed engine power notches and just a few train and locomotive classes have continuously variable engine power control.

[6] Hickman, A., C. Baker, X. Cai, J. Delgado-Saborit, and J. Thornes (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): 1864-1878.

[7] Green, D.C., A. Font, A. Tremper, M. Priestman, D. Marsh, S. Lim, B. Barratt, M. Heal, C. Lin, J. Saunders and D. Pocock (2019). *T1122: Research into air quality in enclosed railway stations*. RSSB.

1.3.2 Previous work in this area

At a rail freight industry-wide workshop in February 2018, hosted by the Freight Transport Association's Rail Freight Council and facilitated by Aether Limited, a methodology to combine existing emissions certification testing from the US (where many GB locomotive and engine designs originate) and elsewhere with on-train monitoring recorder (OTMR) data from GB locomotives was proposed as a cost-effective means of gaining a better understanding of real-world emissions. This has led to freight operating companies (FOC) providing OTMR data (for notch and fuel consumption) to demonstrate a UK proof-of-concept for this methodology to generate much more granular estimates of real-world emissions.

In January 2019 RSSB commissioned a pilot project, RSSB2769 - AQ0001 *Improving Diesel Locomotive Rail Emission Factors - Initial Study*, to develop emission factors as a function of useful energy delivered in different engine notches, not only from freight locomotives, but also from passenger trains (both DMU and locomotive hauled). This approach takes into account the operating characteristics of rolling stock which can be substantially different depending on loadings, stopping patterns and topography.

1.3.3 This project

The previous project developed new emission factors for approximately half of the GB diesel fleet on the basis of estimated total fuel burn. The current project has refined and expanded coverage of emission factor by notch to all main GB rolling stock types. Findings from this project will contribute to the development of the Rail Air Quality Strategy, as well as providing a key foundation for more granular studies of local air quality impacts and benchmarking investment cases for emission reductions measures. This work can guide where further real world testing is needed and it reduces the amount of (expensive) real world testing that would need to be undertaken for each individual train class, since a single set of engine testing results can be used for multiple rolling stock classes.

1.4 Report structure

This report will discuss the merits, derivation, and applications of emission factors by notch. Rail sources of emissions are reviewed in Section 2, including how their production is not necessarily simply related to fuel consumption and power output. Relevant emission standards and their associated regulatory drive cycles (Section 3) are discussed since these can differ substantially from real world engine operation. The history and limitations of current rail emission factors are then covered in Section 4 before the principles and benefits of emission factors by notch are discussed in Section 5. Detailed example calculations are provided for selected locomotives and DMUs (diesel electric, diesel hydraulic and diesel mechanical transmissions) to demonstrate the methodology for developing emission factors by notch (Sections 6, 7 and 8).

An assessment of the GB fleet of diesel trains, engines and transmissions, plus of the emissions testing and OTMR data obtained for this project, is given in Section 9. Situations where proxy factors had to be developed, i.e. where obtaining further data would be beneficial, are identified. Key issues relating to air quality and applications of the new emission factors (including improving those used for the NAEI) are discussed in Section 10. Section 11 is an assessment of non-combustion emissions from rail, setting their importance in the context of all rail emissions. Conclusions, implications for emission reduction strategies, and recommendations for further work are contained in Section 12.

2 Rail sources of emissions

There are two main origins of pollutants emitted to air from combustion sources: air (the source of NO_x), and fuel and engine oil (all other pollutants). This section discusses the origin and formation of the main pollutants emitted from rail sources considered in this project: CO_2, NO_x and PM. Although not the focus of this project, other key air pollutants (CO, SO_2, HC and N_2O) are briefly discussed in this section as how and why they have been reduced is important for understanding how emissions of NO_x and PM are generated, estimated and can be potentially controlled. The origins of pollutants from non-combustion rail sources (abrasion) are discussed in Section 11.

2.1 Carbon dioxide (CO_2) and fuel consumption

With virtually all the carbon in fuel converted to CO_2 during combustion, fuel consumption and emissions CO_2 are intrinsically linked. The combustion of fuel to create useful energy output is not equally efficient under all operating conditions. Hence a detailed understanding of fuel consumption is needed to understand CO_2 production under different operating conditions, including an understanding of combustion efficiency and the energy losses incurred during transmission and supplying auxiliary loads.

Engine fuel efficiency under different operating conditions has traditionally been measured as fuel use per unit energy in g/kWh (also known as brake specific fuel consumption, BSFC, in automotive terminology). Traditionally 200 g of fuel per kWh has been seen as the most efficient a diesel engine for rail use can achieve under a limited range of the most efficient operating conditions at medium and higher power outputs. However, some engines can now attain better than 200 g/kWh under even more limited operating conditions. Outside idle and low power settings real fuel efficiency is in the 170-255 g/kWh range (measured at the engine) or 235-290 g/kWh measured at the wheel (including transmission losses and auxiliary loads). At idle and very lower power engine conditions the fuel consumption can increase to 800-1000 g/kWh when real loads and losses are accounted for, or up to 2500 g/kWh when the engine is set up on a test bed.

For all engines for rail use manufactured in the last few decades, the amount of carbon in fuel leaving the engine as CO_2 is a minimum of ≥98% at idle and a minimum of ≥99.8% under higher power conditions, which allows the specific fuel consumption to be used to accurately calculate CO_2 emissions under a whole range of engine running conditions. A trivial amount of the carbon dioxide comes from the combustion of engine lubricating oil. For newer rail engines with changes to engine design or with abatement solutions fitted, the amount of carbon in fuel leaving the engine as CO_2 is a minimum of 99.9% under the worst operating conditions. However, for CO_2 calculation purposes we have conservatively assumed 100% of fuel carbon is converted to CO_2.

With typical GB rail diesel fuel carbon content in the 84-86.5% range and varying fuel densities and biodiesel content, the fuel:CO_2 ratios lie in a range between 3.05 and 3.13 depending on fuel parameters with most recent detailed engine test data between 3.10 and 3.12.

Most medium-higher power engine operation results in a CO_2 production rate of between 580 and 700 g/kWh when measured at the engine or between 730 and 900 g/kWh when measured at the wheel. At idle and very lower power engine conditions the fuel consumption can increase to 2,450-3,150 g/kWh when real loads and losses are accounted for or up 5,000 g/kWh (small engine) 15,000 g/kWh (large engines) when the engine is set up on a dynamometer test stand.

Figure 1 shows how efficient an engine is at converting fuel to usable mechanical energy (thermal efficiency) conversion efficiency in a well-documented case (EMD Class 66 locomotive and 710 V12 engine). This engine is more efficient at higher power outputs than lower power outputs. Figure 2 shows how efficient the Class 66 locomotive is at transmitting the power from the engine to the wheels (fulfilling other power requirements in real use, such as air compressors, is included in the transmission losses). The proportion of transmission losses is lower at the higher engine power outputs. Overall, then, the conversion of energy in fuel to power at the wheel is most efficient in higher engine power conditions.

Figure 1 Thermal efficiency by engine notch for the EMD 710 V12 engine (as fitted to Classes 66 and 67)

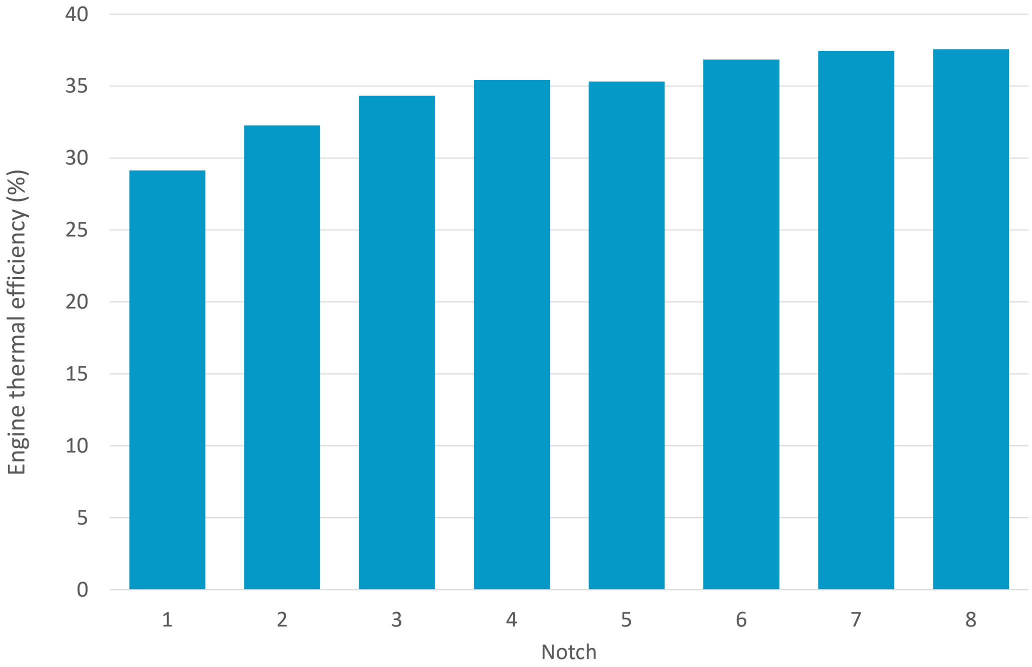
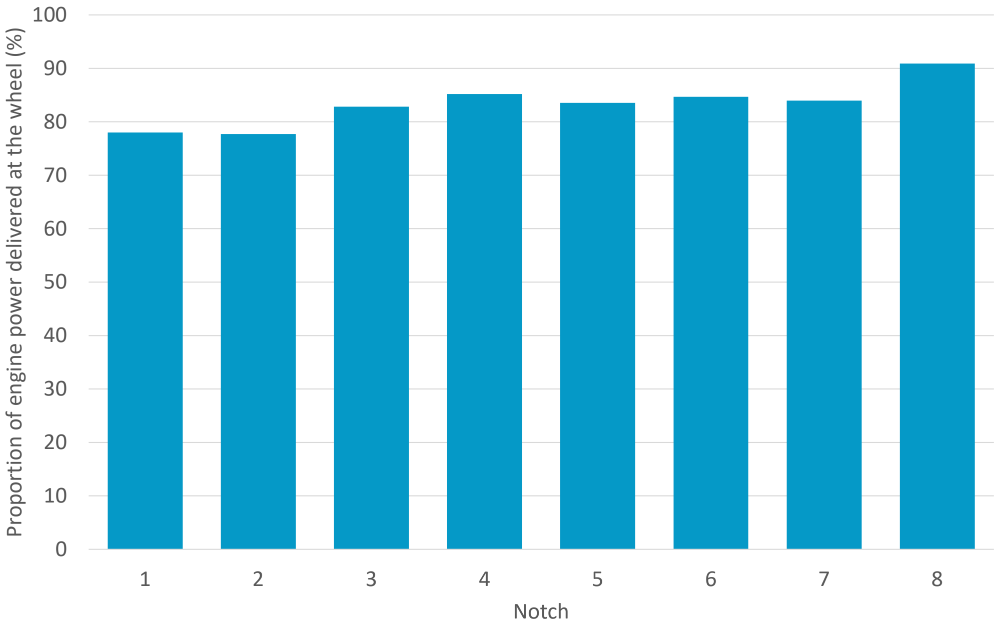


Figure 2 Proportion of engine power delivered at the wheel by engine notch for EMD Class 66



2.2 Sulphur dioxide (SO_2)

Sulphur dioxide (SO_2) is a major air quality pollutant and has significant impacts upon human health. In addition, sulphur dioxide emissions are a precursor to acid rain and atmospheric particulates. Sulphur dioxide is produced from the combustion of sulphur containing compounds in the diesel fuel and the quantity produced is directly related to the fuel sulphur content. Sulphur dioxide and certain other sulphur-containing compounds also inhibit the ability of many platinum and palladium catalysts to convert other air quality pollutants (AQP) to other compounds (this issue is known as catalyst poisoning). For these two reasons most countries have reduced the permitted sulphur content in liquid fuels over time, often in multiple stages with road and non-road fuels reduced at different times. The most recent set of changes in most countries around a decade ago reduced the maximum fuel sulphur content to 10 ppm on a mass basis (15 ppm in US) with this fuel referred to as ultra-low sulphur diesel (ULSD). Previous reductions cut the maximum sulphur content in Europe to 350 ppm in 2000 and 50 ppm in 2005.

In the UK rail diesel fuel is covered in the off-road diesel and fuel oil standard BS 2869 A2[8] which was amended in 2010 to align with required changes under the Fuel Quality Directive (2009/30/EC)[9]. Implementation was required by 1 January 2012 but in practice many UK refineries and suppliers reached compliance earlier and typical UK fuel sulphur levels are lower at around 7.7 ppm. In practice significant volumes of rail diesel fuel supplied in the UK are compliant with the on-road BS EN 590 standard which has some slightly stricter specifications, allowing one fewer fuel product in the supply and distribution system.

Since reducing the sulphur contained in diesel leads to a significant decrease in formation of SO_2, ULSD has virtually eliminated the production of SO_2 by internal combustion engines and as such it is no longer a focus of emissions regulations.

2.3 Carbon monoxide (CO)

Carbon monoxide (CO) is the air quality pollutant (AQP) that is produced in the largest quantities but it has less significant impacts upon human health and the formation of other secondary AQPs than NO_x, PM, SO_2 or hydrocarbons (including VOC). Development of emission factors by notch for CO was not in the scope of this project.

CO is formed as a result of incomplete combustion due to three main factors:

- insufficient oxygen (including localised effects within the cylinder)
- a drop in temperature before the combustion process is complete
- the presence of carbon-containing compounds that are harder to combust.

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[8] British Standards Institute (2017). *BS 2869:2017 Fuel oils for agricultural, domestic and industrial engines and boilers*.

[9] https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0088:0113:EN:PDF

Although there are many complex interlinked underlying factors, CO formation is relatively well understood. This has allowed solutions to reduce CO emissions to be easily implemented on engines compared to other pollutants. Many of the underlying drivers for CO formation are identical or similar to those for hydrocarbons (HC) formation (Section 2.6), allowing both CO and HC reductions to be addressed by the same solutions.

There are three main routes to reducing CO emissions:

1. Ensuring more complete combustion occurs initially within the cylinder for example through the use of better turbochargers (to increase oxygen levels) and improved fuel injection technology (to enable better distribution of fuel in the cylinder and faster better-timed fuel injection). This has significantly reduced the production of CO from low-medium to full power engine operating conditions but is less effective at reducing CO production at the lowest engine power.
2. The use of Diesel Oxidation Catalyst (DOC) abatement technology (in the exhaust system), which can substantially reduce any remaining carbon monoxide. The catalyst in the DOC technology is poisoned by sulphur dioxide and other sulphur-containing compounds hence a prerequisite for adopting DOC is the use of ULSD. The DOC technology works by fully oxidising partially oxidised CO (to CO_2) and NO (to NO_2 as a precursor to selective catalytic reduction, SCR, which is used to reduce NO_x) and by burning remaining hydrocarbons (producing CO_2 and H_2O) and soluble organic fraction particulate matter (producing CO_2 and H_2O). DOC abatement technology is a useful broad-spectrum solution for reducing emissions of many AQPs and since all DOC reactions are exothermic increasing the exhaust temperature, it can aid the use and effectiveness of SCR or diesel particulate filter (DPF).
3. Improvements in fuel quality that reduce the levels of compounds in the fuel that are harder to combust. For example, poly aromatic hydrocarbons (PAH), which do not burn well, now constitute a maximum of 8% of diesel after the BS EN590 and BS 2869 A2 fuel specification changes a decade ago (previously the maximum permitted level was ~15%).

Despite being the AQP with the highest volume of emissions produced by rail, significant reductions in carbon monoxide emissions have been achieved with no impact on fuel consumption.

- Older engines typically have CO emissions (as a % of total combustion emissions by mass) of up to 1.25% at idle and low power and below 0.3% at medium and high-power conditions.
- Newer engines without DOC will typically have CO emissions of up to 0.6% at idle and low power and below 0.05% at medium and high-power conditions.
- Newer engines with DOC fitted will typically have CO emissions of 0.01% at idle and low power and below 0.04% at medium and high-power conditions.

While included in current emission standards, the challenges of lowering CO emissions started to be met in practice 25 years ago or earlier with CO emissions in practice substantially below regulatory limits hence those carbon monoxide emissions of this pollutant are no longer seen as needing prioritising for any further action, with more recent indirect improvement coming as a consequence of actions focusing on reducing other AQPs.

2.4 Nitrogen oxides (NO_x)

Nitric oxide (NO) and nitrogen dioxide (NO_2) are collectively referred to as NO_x. A third nitrogen oxide, nitrous oxide or N_2O, is also created during combustion. N_2O is not an air quality pollutant but is a greenhouse gas (GHG) with a global warming potential that is 298 times that of CO_2.

2.4.1 NO_x formation

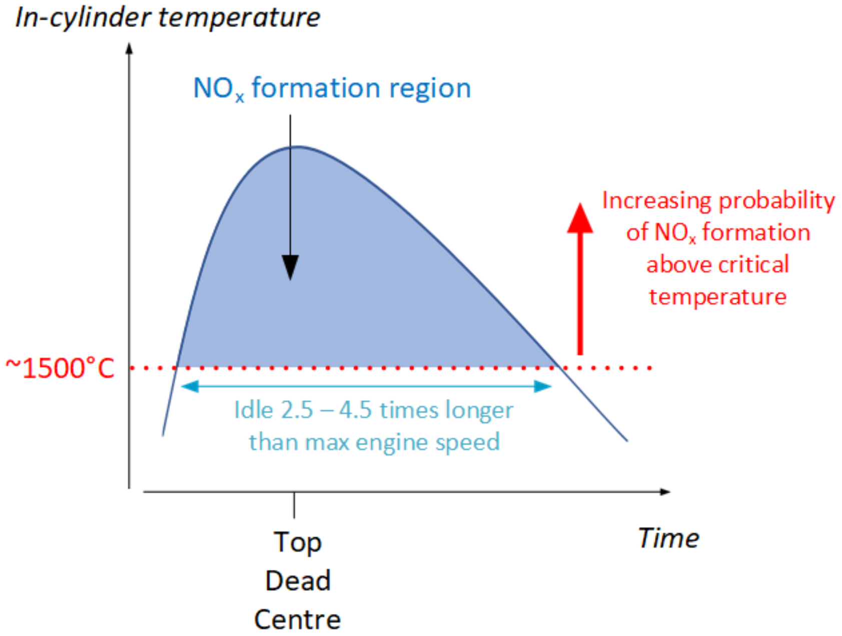
NO forms in an engine cylinder above a critical temperature (~1500°C) behind the propagating combustion flame front where the temperatures are highest. Above ~1500°C the geometry of the most stable arrangement of the N_2 triple bond is different and the nitrogen molecules try to readjust to this arrangement. At the moment of readjustment, the nitrogen molecule is vulnerable to attack by oxygen to form NO.

- The greater the temperature (above the critical level), the more likely it is that the nitrogen molecules will attempt to rearrange the bond.
- The greater the oxygen partial pressure, the greater the probability of successful attack by an oxygen molecule to form NO at the critical moment the nitrogen molecules are attempting to rearrange the bond.

Some NO is immediately converted in the cylinder to NO_2 and N_2O. The time spent above the critical temperature dictates the total amount of NO_x formed. Some NO is then later converted to NO_2 and N_2O in the exhaust and later photochemically in the atmosphere to ozone (O_3). Nitrogen oxides are fairly stable at room temperature and pressure with a typical lifespan of 100+ years.

In contrast to SO_2, formation of NO_x depends not just on what is combusted but how the combustion process takes place. Figure 3 shows the NO_x formation region in relation to cylinder temperature and the timing of the combustion cycle. Both increased temperature and increased pressure increase the probability of NO_x formation. Strategies used by engine manufacturers to reduce NO_x generation focus on reducing the size and/or altering the shape of the shaded area in Figure 3 (and are discussed later).

Figure 3 NO$_x$ formation in relation to cylinder temperature and engine timing

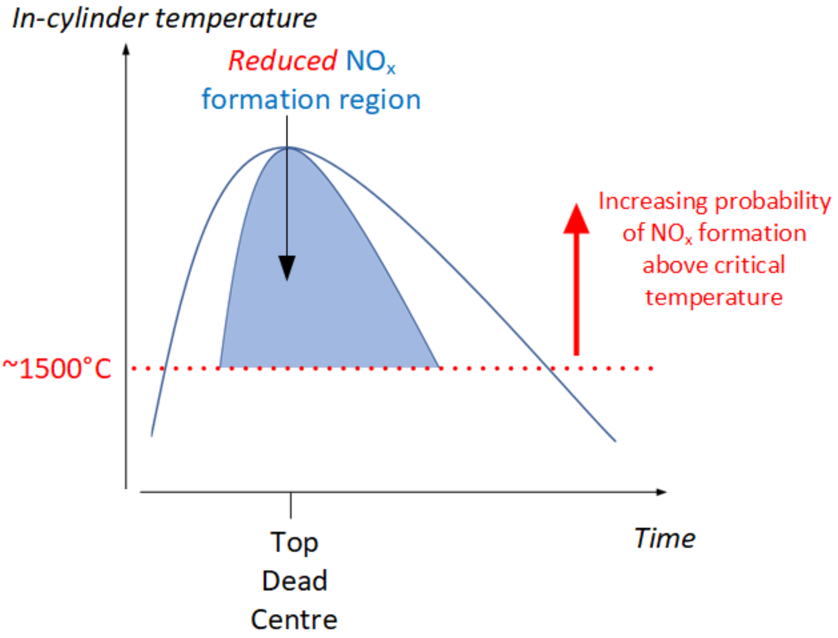


There are seven key drivers for NO$_x$ production:

- **Time above critical temperature**: Time above ~1500°C and at high pressure (maximised at low engine speeds as the time in cylinder at high temperatures is much longer). The longer the time the greater the chance of chemical reaction occurring. Figure 4 shows the effect of increasing the engine speed on the time available for NO$_x$ to form.

  This means idle and low engine speed is bad for NO$_x$ production.

Figure 4 Effect of increasing engine speed on NO_x formation in relation to cylinder temperature and engine timing



- **Oxygen level (or remaining oxygen level):** Lean combustion, i.e. having excess air in the cylinder compared to the ideal air fuel ratio range; this has the secondary effect of increasing the temperature by up to 250°C. To reduce fuel consumption and running costs at idle the minimum quantity of fuel is used and this has fallen over time with improved fuel injection. Also, turbo and supercharger designs are optimised for high power output conditions and hence they supply far more air than required at low power (idle). A small reduction in the concentration of oxygen e.g. from 21.5% in the ambient air to just 18% dramatically reduces the probability of NO_x formation. This occurs after about a quarter of the combustion has occurred at full power but never at idle. Another way of achieving this reduction at low engine power conditions is to use exhaust gas recirculation (EGR) where a small amount of the exhaust gas stream is diverted, then cooled and added to the intake air to dilute the oxygen level down to around 18%.

  This means idle, low power and low engine speed is bad for NOx production.

- **Pressure:** Pressure plays a key role in the probability of the rate-limiting NO formation step. The greater the oxygen (partial) pressure the greater the chance of NO formation as there is a greater chance of oxygen being in proximity when the nitrogen molecules try to rearrange to a more stable bond above 1500°C. Unfortunately, high pressures are a fundamental requirement of compression ignition (diesel) engines so this is very difficult to manage but can be addressed via lower effective compression ratios and greater boost from the turbo instead (e.g. Miller Cycle which is discussed later in this section).

This means high efficiency combustion is often bad for NOx production.

- **In-cylinder turbulence/mixing:** Turbulence in the cylinder (which is highest at higher engine speeds) improves combustion which both reduces high local temperatures where there is poor combustion and reduces the oxygen level faster.

  This means idle and low power is bad for NOx production.

- **CO_2 levels.** CO_2 has significantly higher specific heat capacity than the other in cylinder gases, hence it is better at absorbing heat, so the temperature rises are smaller with greater CO_2 concentration. The use of EGR, where a small amount of the exhaust gas stream is diverted then cooled and added to the intake air, increases CO_2 levels in the intake air before combustion, especially at lower engine powers, which reduces the in-cylinder temperature.

  This means idle and low power is bad for NOx production.

- **Uneven fuel distribution:** Uneven fuel distribution leading to ultra-lean combustion in small localised regions within the cylinder occurs for different reasons at high engine speeds (turbulence due to higher piston speed) than at low engine speeds (injector fuel distribution pattern). These issues can be improved by higher pressure injection, more sophisticated nozzle design and with electronic fuel injection combined with computer control variable injection timing, variable duration, variable injection shape and multi shot injection.

  This means older low-pressure injection technology is bad for NOx production.

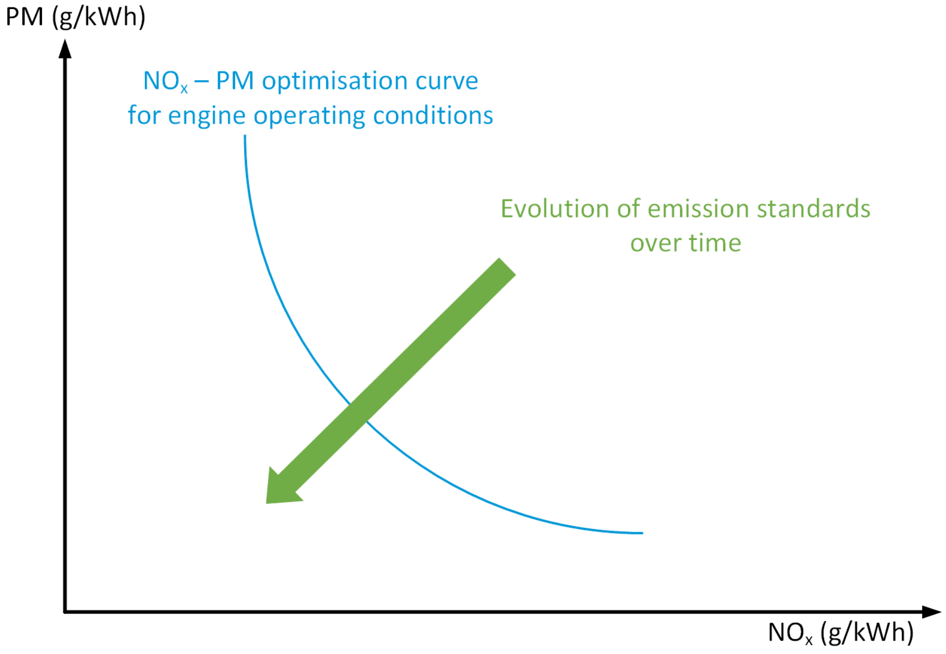
- **Fuel components that do not combust well:** Certain fuel components, such as poly aromatic hydrocarbons (PAH) do not combust well raising localised temperatures further.

  This means higher PAH levels are bad for NOx production.

A crucially important observation is that five of the seven main drivers behind NO_X production result in higher NO_x production per unit energy output at idle or lower engine power outputs. Hence comparatively more NO_X is produced at idle than at other (higher) engine power conditions, i.e., there is a not a linear relationship between NO_x production and fuel consumption. This issue is discussed further in this section and forms a prominent theme throughout this report.

There is a relationship between the production of elemental carbon (EC) particulates (see Section 2.5 on PM) and all oxides of nitrogen when internal engine measures are used — if fewer EC particulates are produced during the combustion process (by increasing temperature so both fewer are formed and more are fully burnt before leaving the cylinder), the quantity of NO_x also increases, and vice versa. Therefore, if the aim is to significantly minimise both NO_x and EC emissions, it is difficult to achieve this without some abatement measures for one or more of these pollutants.

Figure 5 Trade-off relationship for NO_x versus elemental carbon PM production



2.4.2 Approaches to reduce NO_x emissions

In order to achieve compliance with increasingly strict emission regulations around the world, engine manufacturers aim to reduce emissions of elemental carbon soot particles and NO_x mainly by low-emission combustion, in other words, through internal engine solutions. However, this means taking into account a basic principle that governs the process of combustion: if the fuel burns at a higher temperature inside the cylinder, little soot (EC), but a large amount of NO_x, is produced. Whereas at lower combustion temperatures, NO_x emissions are low, but the production of soot is high. To find the right balance, therefore, all the key technologies that affect combustion must be aligned and optimised. The remainder of emissions can then mostly be reduced post combustion by abatement. Thus, cutting the volumes of emissions produced in the first instance reduces the quantity of abatement then needed.

There are five main approaches to reduce in engine NO_x production:

2.4.2.1 Exhaust Gas Recirculation

The main method of significantly reducing NO_x emissions by using internal engine technology involves cooling some of the exhaust gas, which is then redirected back into the charge air reducing the oxygen levels, a process known as exhaust gas recirculation (EGR). This results in a reduction in the oxygen partial pressure, which directly slows the rate of both combustion and NO_x formation. The slower combustion which results from a lower peak flame temperature in the combustion chamber also reduces the rate of NO_x formation. CO_2 also has a higher specific heat capacity than the other gases and its addition to the charge air helps decrease the temperature rise that results from compression and combustion, which also reduces the rate of NO_x formation. Reducing the oxygen level from the normal atmospheric 20.5-21% to 17-18% can produce a five-fold reduction in NO_x production. While EGR is more effective at high engine power for a given proportion of recirculation it also works at low engine powers unlike the other significant NO_x reduction method - SCR, an aftertreatment abatement measure. At lower power outputs a greater proportion of EGR can be used (and at lower pressures too) making it easier to implement. These two temperature-reduction and one oxygen partial pressure related mechanisms dramatically reduce the production of NO_x by up to 40% in rail-sized diesel engines.

While SCR systems can remove up to 90% of the NO_x from exhaust gases they can only do so at medium and high exhaust temperatures and not at low exhaust temperatures that usually correlate with low power conditions including idle. Hence EGR is the only significant reduction method available for low engine power conditions. EGR was first introduced on some rail engines subject to EU Stage IIIB or US Tier 3 emission standards which came into force in 2012 (see Section 3).

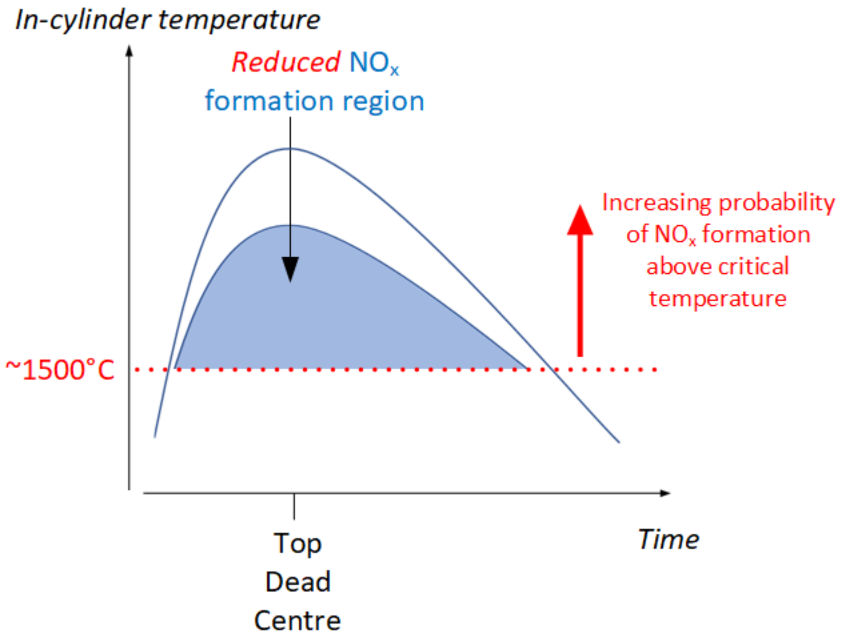
EGR places additional demands on exhaust gas turbocharging, since higher boost pressures have to be achieved with reduced mass flow in the turbocharging system. These higher boost pressures are required to direct the increased mass flow resulting from the exhaust gas recirculation rate into the cylinder during the combustion cycle. In addition, the exhaust gas can only be redirected back into the cylinders when there is a pressure drop between the exhaust and the charge air systems. This pressure drop must be established with an appropriately configured turbo charging system, which results in a reduction in turbocharging efficiency. The pressure drop between the exhaust and the charge air systems leads to thermodynamic cycle losses. These factors tend to result in lower engine performance or higher fuel consumption.

The exhaust gas drawn off for recirculation in a rail diesel engine has a temperature of up to 650°C. This is far too hot to be fed directly into the cylinders; it would increase the temperature of the combustion chamber even further, thereby defeating its actual purpose - that of reducing NO_x formation by lowering the combustion temperature. For this reason, the exhaust gas is first cooled to around 120°C. The modifications to the engine to fit EGR have relatively small space requirements which is an important issue given the limited British loading gauge. However, it is necessary to modify the cooling and radiator systems in order to cope with the increased cooling requirements. A problem with EGR is that particulate matter can build-up on components (e.g. the valve in the exhaust system) increasing the amount of servicing required and decreasing the inspection or servicing intervals.

2.4.2.2 Charge air cooling and/or inter-cooling

Charge air cooling involves cooling the air between the turbocharger and the engine, while inter-cooling involves cooling the air between the stages of a multi-stage turbocharger. While the air temperature reductions in rail type engines are only a modest 10-20°C, this temperature reduction is also seen in the maximum in-cylinder temperatures (Figure 6) thus providing a modest reduction in NO_x formation rate. Like EGR it requires a larger more complicated cooling system.

Figure 6 Effect of using charge air cooling or intercooling on NO_x formation in relation to cylinder temperature and engine timing



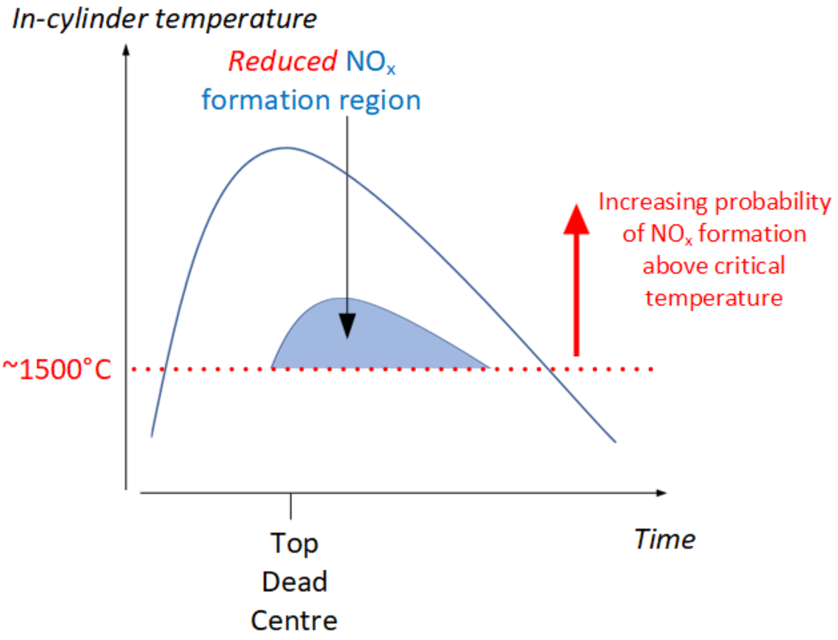
2.4.2.3 Injection timing

Modern computer controlled high-pressure fuel injection systems can be used to precisely control the timing and fuel injection rates which can be adjusted to reduce NO_x or PM formation (or occasionally both!). In general, increasing the fuel injection pressure and improving the fuel spray pattern to improve fuel distribution for more even combustion can reduce NO_x and PM production. However, adjusting the timing and fuel injection rates usually mean what measures are effective for reducing NO_x also increase PM and vice versa. Most NO_x is formed early on within just 20° of engine rotation hence strategies to reduce NO_x formation have typically involved injecting fuel later or in a more sophisticated way. The aim to have a slow fuel injection rate earlier in the cycle and a higher fuel injection rate later through either injection rate shaping or multi injection. Injection timing solutions are only capable of reducing NO_x to meet Euro Stage IIIA or US Tier 3 emission standards and are also accompanied by small reductions in fuel efficiency.

2.4.2.4 Miller Cycle

Using the Miller thermodynamic cycle to reduce NO_x involves reducing the in-cylinder compression ratio and thus the temperature rise from compressing the air to the same extent (without changing the expansion ratio). This is achieved by adjusting the inlet valve timing so the valves either close earlier or later than at the time needed for maximum compression. This is typically set up to reduce the compression ratio by about a quarter, resulting in a smaller increase in air temperature due to less compression with a smaller pressure rise occurring. The potential downside is that there is far less air for efficient combustion at higher engine power outputs, but this can be compensated for by using multistage turbochargers and charger air cooling and inter-cooling. Thus the same combustion condition pressures can be maintained with the turbocharger increasing the effective compression ratio back to non-Miller cycle levels but with lower in-cylinder temperatures. As the compression rate is slower (and the expansion rate is relatively higher), the combustion occurs more slowly which also leads to a smaller temperature rise, so minimising NO_x formation (illustrated in Figure 7).

Figure 7 Effect of using the Miller cycle on NO_x formation in relation to cylinder temperature and engine timing



2.4.2.5 Turbocharger design changes

Single compression stage turbochargers can only effectively be optimised to minimise high NO_x production conditions for a relatively small proportion of the engine speeds (at high power conditions). This usually results in significantly higher charge air volumes (high air: fuel ratios and ultra-lean combustion conditions) than required at low engine speeds and powers, which results in higher NO_x production. Optimising air volumes across a broader range of engine conditions requires using a multi-stage turbocharger (typically two-stage which enables higher air pressures to be produced across a range of engine conditions while optimising the air volume). This process involves initial compression of the intake air by low-pressure turbochargers followed by further compression in high-pressure turbochargers. Multi-stage turbochargers are better able to cope with increased backpressures that come with using engine technologies such as EGR, Miller cycle or abatement technologies such as DOC, DPF and SCR, and also allow greater charge air cooling.

2.4.2.6 NO_x abatement

There is just one main approach to reduce NO_x with abatement which is SCR, an exhaust gas abatement. SCR employs chemical reduction to render nitrogen oxides harmless and involves a chemical reaction in which NO_x in exhaust gas are converted into water (H_2O) and nitrogen (N_2). For this purpose, urea-water solution (a reducing agent) is continually injected into the exhaust gas flow upstream of the SCR catalytic converter into the exhaust gas flow in a carefully metered manner. The fluid reacts to produce ammonia (NH_3) which then reduces the nitrogen oxides (both NO and NO_2) in the SCR catalytic converter.

The SCR process is endothermic (it absorbs energy unlike other abatement technologies) and the reactions only occur at medium and high exhaust temperatures. This means that SCR is not effective at removing NO_x at low exhaust temperatures e.g. under low engine power conditions including Idle. Higher overall conversion rates of NO_x to H_2O and N_2 occur if the quantities of NO and NO_2 are approximately matched, however the proportion of NO is usually much greater than that of NO_2.

Both problems can be partially addressed with the use of DOC abatement technology positioned in the exhaust system before the SCR. DOC works by fully oxidising partially oxidised CO (to CO_2), NO (to NO_2) and by burning remaining hydrocarbons (producing CO_2 and H_2O) and soluble organic fraction particulate matter (producing CO_2 and H_2O) – these reactions both increases the exhaust gas temperature and the quantity of NO_2 allowing greater and more efficient conversion to occur. However, the low exhaust temperature problem is not entirely solved as the temperature increase and extra energy in the exhaust gas stream from the DOC technology is still not sufficient at the lowest engine powers to raise the exhaust temperature for SCR to work. SCR can remove up to 90% of the NO_x produced during the combustion process from the exhaust gas, but not at low exhaust temperatures or low engine power conditions including idle. Hence if there is a desire to reduce NO_x at low power outputs other methods need to be used.

The urea-water solution used for SCR is a non-toxic and odourless reducing agent. It is widely used in commercial vehicle applications and has been available throughout Europe since 2004, marketed under the trade name of 'Ad Blue' or as 'Diesel Exhaust Fluid' and consists of a 32.5% solution of urea in de-ionized water. The quantity of reducing agent added is about 5 to 7% percent of the average fuel consumption.

Consequently, it is necessary to have a robust and detailed understanding of how, when and where emissions of air pollutants are generated by rail diesel engines and to therefore understand the exact impact of proposed measures. Disregarding such a detailed approach may lead to ineffective measures to address air quality. It is important to note that:

- Older engines typically have NO_x emissions (as a percentage of total combustion emissions by mass) in the 2.2-2.8% range at idle and low power and in the 1.3-2.0% range at medium and high-power conditions.
- Newer engines with SCR fitted typically have NO_x emissions (as a percentage of total combustion emissions by mass) of 1.8-2.0% at idle and low power, and below 0.5% at medium and high-power conditions.

2.5 Particulate matter

Rail sources of atmospheric particulate matter (PM) are combustion (the main diesel traction source) and abrasion (of rail, wheels, brakes, pantographs and ballast). Combustion particulate emissions are discussed in this section and abrasion particulate emissions are discussed in Section 11.

2.5.1 PM size fractions

PM is made up of a collection of solid and/or liquid materials of various sizes from a few nanometres in diameter (about the size of a virus) to around 100 micrometres (100 µm, about the thickness of hair). As well as health effects from direct inhalation some types of PM can also have impacts on climate and precipitation.

In general, the smaller and lighter a particle is, the longer it will stay in the air. Larger particles e.g. greater than 10 micrometres (µm) in diameter tend to settle to the ground by gravity in a matter of hours whereas the smallest particles e.g. less than 1 micrometre (µm) can stay in the atmosphere for weeks and are mostly removed by precipitation.

There are two common size classifications of particulate matter that are widely measured:

- PM_{10} - medium particles with a diameter of ≤10 µm.
- $PM_{2.5}$ - fine particles with a diameter of ≤2.5 µm. $PM_{2.5}$ is a sub-set of PM_{10}.

In almost all testing of rail engines only PM_{10} is measured and so all references to PM in this report are PM_{10} unless otherwise stated.

Even finer particulates are sometimes measured in specialist studies. These include:

- $PM_{1.0}$ - finer particles with a diameter of 1.0 µm or less. $PM_{1.0}$ is a sub-set of $PM_{2.5}$.
- $PM_{0.1}$ - finest particles with a diameter of 0.1 µm or less. $PM_{0.1}$ is a sub-set of $PM_{1.0}$.

Some detailed studies also measure total suspended particulate matter (TSP) which include particulates of all sizes, i.e. including those larger than PM_{10}, but the measurement of larger particles is can be subjective as these tend not to travel far and settle quickly.

In cases where only PM_{10} is measured, as estimate of $PM_{2.5}$ can made using a ratio based on detailed studies. The European Monitoring and Evaluation Programme/European Environment Agency (EMEP/EEA) Air Pollutant Emission Inventory Guidebook[10], which is normally the source of suitable default values used in Europe, suggests a value of 95%, i.e. 95% of the particulate material ≤10 µm is also less than ≤2.5 µm. The source for this ratio is the UIC Emission Work Package 4 Report[11] from 2005-2006 which used 95% based on rounding-up 94% from a 1999 UK Airborne Particles Expert Group (APEG) report[12] from 1999. The source of the APEG ratio is the now retired Volume II of the US Environmental Protection Agency (EPA) AP-42 Compilation of Air Emissions Factors[13] (the US equivalent of the EMEP/EEA Emission Inventory Guidebook). This value was a generalised non-road equipment ratio including non-combustion particulates as the APEG also wanted to include non-combustion emissions. A more appropriate diesel engine-only non-road equipment ratio from Appendix B.2 of AP-42 is 90% which is based on some 1979 and 1985 work[14], [15].

A separate US EPA rail (locomotive) combustion $PM_{2.5}$:PM_{10} ratio (that is still currently used) of 97% is given in a US EPA regulatory support document from 1998[16] but the source of the ratio is unreferenced in that document.

Several more recent studies[17], [18], [19], [20] which included results for more modern engines where attempts have been made to reduce PM emissions, report lower ratios in the 55-80% range. The likely difference with earlier studies is that the reduction in combustion PM to comply with stricter emission standards has come from reducing the number of smaller and medium sized particles, which would have reduced the ratio from the 1990s values.

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[10] https://www.eea.europa.eu/publications/emep-eea-guidebook-2019

[11] Kollamthodi, S. and T. Hazeldine, (2006). *Rail Diesel Study, WP4 Draft Interim Report: Possible emission reduction strategies that could be applied to diesel traction units across the 'EU Railway 27'.* UIC.

[12] Airborne Particles Expert Group (1999). *Source apportionment of airborne particulate matter in the United Kingdom*. Department of the Environment, Transport and the Regions.

[13] https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors

[14] Taback, H. J. et al. (1979). *Fine particulate emissions from stationary sources in the South Coast Air Basin*. KVB, Inc., Tustin, California.

[15] US EPA (1985). *Fine Particle Emission Inventory System*. Office Of Research And Development.

[16] US EPA (1998). *Locomotive Emission Standards: Regulatory Support Document*. EPA-420-R-98-101.

[17] Jaffe, D. A., G. Hof, S. Malashanka, J. Putz, J. Thayer, J.L. Fry, B. Ayres and J.R. Pierce (2014). 'Diesel particulate matter emission factors and air quality implications from in-service rail in Washington State, USA', *Atmospheric Pollution Research* 5(2): 344-351.

[18] Abbasi, S., A. Jansson, U. Sellgren and U. Olofsson (2013). 'Particle emissions from rail traffic: A literature review', *Critical Reviews in Environmental Science and Technology* 43(23): 2511-2544.

[19] Ruehl, C., J.D. Herner, S. Yoon, J.F. Collins, C. Misra, K. Na, W.H. Robertson, S. Biswas, M.-C.O Chang and A. Ayala (2015). 'Similarities and Differences Between 'Traditional' and 'Clean' Diesel PM', *Emission Control Science and Technology* 1: 17-23.

[20] Hickman, A., C. Baker, X. Cai, J. Delgado-Saborit, and J. Thornes (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): 1864-1878.

Two recent sets of UK work have found lower $PM_{2.5}$:PM_{10} ratio values:

- University of Birmingham study[21] at Birmingham New Street: ratios in the range of 72-79%.
- RSSB T1122 study[22] at Edinburgh Waverley and London Kings Cross: ratios in the range of 11-79% with a value of 79% on the Platform 0/1 island at Kings Cross.

The Birmingham New Street study derived an average ratio of 74.5% and we recommend that wherever a $PM_{2.5}$ value is needed this ratio be used until a broader range of engine-specific testing for $PM_{2.5}$ is carried out.

2.5.2 PM combustion sources

Combustion PM has multiple origins. Although most soot formed during initial combustion is later burnt, some is not and acts as nucleating sites for condensing gases (mostly heavier unburnt or partially combusted hydrocarbons). The condensing material is a mix of:

- Unburnt or partially burnt hydrocarbons
- Poly aromatic hydrocarbons (PAH). A sub-set of unburnt or partially burnt hydrocarbons. With recent changes to fuel standards these now constitute a maximum of 8% of diesel and do not burn well.
- Oxygenated hydrocarbons
- Sulphur compounds.

Particulate formation is a multistage process with distinct phases and conditions:

1. Nucleation – formation of EC particles (soot) from poorly combusting precursor material including PAH above 1050°C. The particles at this stage are typically in the size range 5-50 nm.
2. Growth – the soot particle mass increases through surface growth of all PM components. The particles at this stage are typically in the size range 100-300 nm which represent 80-90% of combustion PM particles.
3. Agglomeration – a limited number of separate particulates merge to form much larger coarse particles. The particles at this stage are typically >1 µm.

These later processes mostly occur at lower temperatures than nucleation step, and often happen away from high-temperature zones. The progress rates of the soot formation processes, from nucleation, growth and agglomeration, increase with the concentration of the reactants involved, such that other factors being equal, more fuel-rich mixtures generally form soot more quickly (while ultra-lean conditions at idle may

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[21] Ibid.

[22] Green, D.C., A. Font, A. Tremper, M. Priestman, D. Marsh, S. Lim, B. Barratt, M. Heal, C. Lin, J. Saunders and D. Pocock (2019). *T1122: Research into air quality in enclosed railway stations*. RSSB.

help reduce PM formation, it will also encourage NO_x formation). The presence of sufficient oxygen species local to the PM formation halts the processes.

At lower engine speeds there is longer time for the condensation process to occur and it is easier for PM to remain in the cylinder for multiple combustion cycles enabling the particles to grow far larger and heavier as the conditions are more benign for doing so.

Combustion particulate matter is usually classified chemically into four categories:

- Elemental carbon (EC, also known as black carbon) – virtually pure carbon soot.
- Organic carbon (OC, also known as soluble organic fraction) – unburnt and/or partially burnt hydrocarbons from lubricant (~80%) and fuel (~20%).
- Ash – the residual inorganic mineral content including oxidised metallic particle residues (including material lost for catalysts). Common elements in ash include Ca, Cu, Fe, Mg, Mo, Si, P and Zn and if catalyst systems are fitted include Pd, Pt and Rh too.
- Sulphates and water – burnt fuel sulphur content residues, which due to their chemical nature tend to absorb water. Sulphur-containing molecules act as nucleating sites for other material to condense on.

The sulphate component of the combustion PM has now been virtually eliminated because of the changes to the diesel fuel standards from 2000, 2005 and 2012 to align with the reduced fuel sulphur content in road ultra-low sulphur diesel (ULSD). Consequently, there has been around a 20% reduction in PM emissions from rail diesel engines when swapping from the oldest to newest fuels. This has important implications when considering and comparing emission testing results from before and after these fuel standard changes.

Reducing the fuel sulphur content also substantially reduces the water content contained in PM as the other components are far less likely to absorb water. As well as requiring reduction in sulphur content, the introduction of the current rail fuel specification (matching road specification fuel) has also involved the addition of cetane enhancers to the fuel which promote an earlier and slower start to combustion reducing the production of particulates (and NO_X). The processes used in refineries to reduce fuel sulphur levels also have the beneficial side-effect of moderately reducing the polycyclic aromatic hydrocarbons (PAH) content of the fuel, which in turn leads to reduced particulate and NO_X formation. PAH which do not burn well, now constitute a maximum of 8% of diesel after the BS EN590/BS 2869 A2 fuel specification changes a decade ago (previously the maximum permitted level was ~15%).

Further PAH content reduction would also see further reductions in PM and NO_X – see for example the Swedish Transportation Administration study[23] on the use of Mk1 specification diesel (which has ≤0.5% PAH content) in Sweden over the last two decades.

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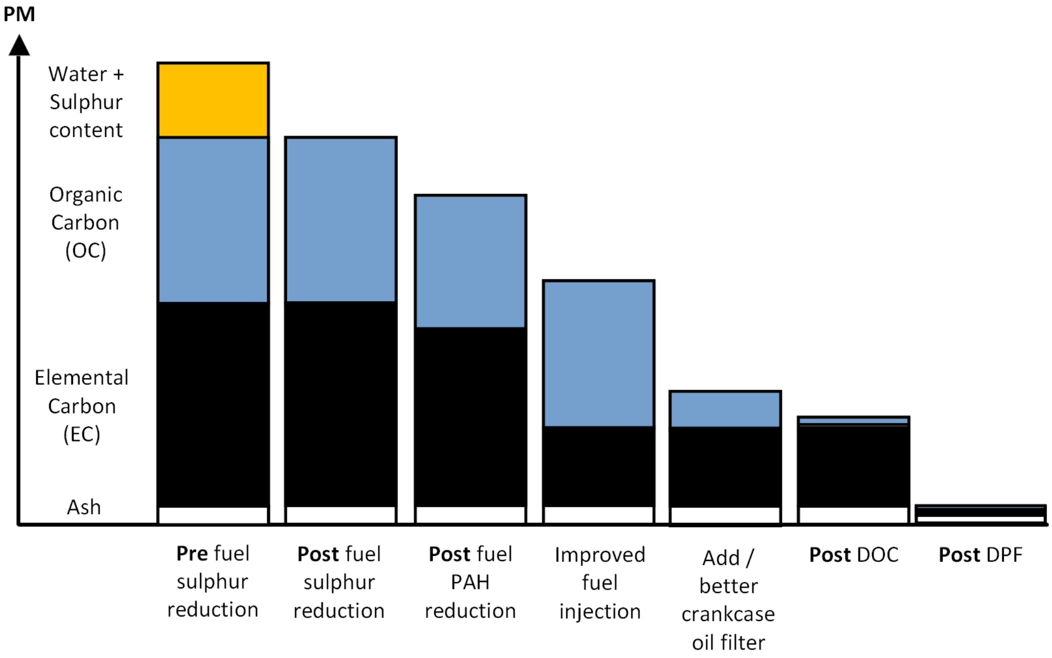
[23] Danielsson, D. and L. Erlandsson (2010). *Comparing Exhaust Emissions from Heavy Duty Diesel Engines using EN590 vs. MK1 Diesel*. Swedish Transportation Administration.

The largest components of combustion particulate matter are elemental carbon and organic carbon, with US rail engine testing[24] indicating an average 55:45 split in terms of carbon content based on in-notch testing and rail drive cycles without the use of any abatement. The content of typical rail combustion PM depending on variations in fuel specification and technological solutions[25, 26, 27, 28, 29, 30] is shown in Figure 8 .

Figure 8 PM content and emission reduction strategies



There have been six main routes to reducing PM emissions:

1. Ensuring that less lubricating oil escapes into the exhaust stream, for example by fitting crankcase oil mist filters (or upgrading to better filters which are more effective at removing smaller oil droplets) or changes to the cylinder liner and piston rings. This can cut organic carbon and ash PM emissions.

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[24] Bohac, S.V., E. Feiler, and I. Bradbury (2012). 'Effect of injection timing on combustion, NO_x, particulate matter and soluble organic fraction composition in a 2-Stroke Tier 0+ locomotive engine', *Journal of Engineering for Gas Turbines and Power*, 135(1).

[25] Ibid.

[26] McDonald, J., D. Osborne and I. Khalek (2009). 'The composition of particulate matter emissions from two Tier 2 locomotives', *Proceedings of the Air and Waste Management Association's Annual Conference and Exhibition*, AWMA, Vol. 3.

[27] Jaffe, D. A., G. Hof, S. Malashanka, J. Putz, J. Thayer, J.L. Fry, B. Ayres and J.R. Pierce (2014). 'Diesel particulate matter emission factors and air quality implications from in-service rail in Washington State, USA', *Atmospheric Pollution Research* 5(2): 344-351.

[28] https://www.mtu-solutions.com/nea/en/stories/technology/research-development/how-does-a-diesel-particulate-filter-work.html

[29] Ruehl, C., J.D. Herner, S. Yoon, J.F. Collins, C. Misra, K. Na, W.H. Robertson, S. Biswas, M.-C.O Chang and A. Ayala (2015). 'Similarities and Differences Between 'Traditional' and 'Clean' Diesel PM', *Emission Control Science and Technology* 1: 17-23.

[30] http://s7d2.scene7.com/is/content/Caterpillar/C10798045

2. Improvements in fuel quality, for example reducing the levels of certain compounds in the fuel that do not combust well, such as poly aromatic hydrocarbons, so reducing both elemental carbon and organic carbon PM.
3. Increasing combustion temperature, which both reduces the formation of elemental carbon and increases the combustion of any that is formed. This however conflicts with measures to decrease NO_x emissions since NO_x formation increases with increasing temperature.
4. The use of Diesel Oxidation Catalyst (DOC) abatement technology (in the exhaust system), which can substantially reduce most organic carbon emissions. (DOC is covered in detail in Section 2.3.) In the organic carbon case, the DOC technology works by burning (fully or partially) the remaining hydrocarbons (producing CO_2 and H_2O in the fully combusted case). DOC also requires slightly above minimal exhaust temperatures to operate hence they tend not to work for idle conditions unless idle settings are substantially altered at the cost of increased fuel consumption. A key difference between elemental carbon and organic carbon is that the latter can be removed with DOC unlike the former.
5. Ensuring more complete combustion occurs initially within the cylinder for example improved fuel injection technology (to enable a finer and more even distribution of fuel in the cylinder and faster better-timed fuel injection). This has reduced the production of soot (elemental carbon) on which other components of PM can then grow.
6. Fitting a diesel particulate filter (DPF) system can remove virtually all EC particulates emitted in the exhaust but this will typically be far less effective at removing OC, ash or sulphate-containing PM. There is a relationship between the production of EC particulates and nitrogen oxides when internal engine measures are used — if fewer EC particulates are produced during the combustion process (by increasing temperature so both fewer are formed and more are fully burnt before leaving the cylinder), the quantity of nitrogen oxides also increases, and vice versa. Therefore, if the aim is reducing both EC and NO_x substantially, because reducing production of EC PM to the lowest possible levels is not possible at the same time as trying to lower NO_x, from the exhaust, then adding a DPF is necessary. A DPF can remove 90 percent or more of the EC particulates.

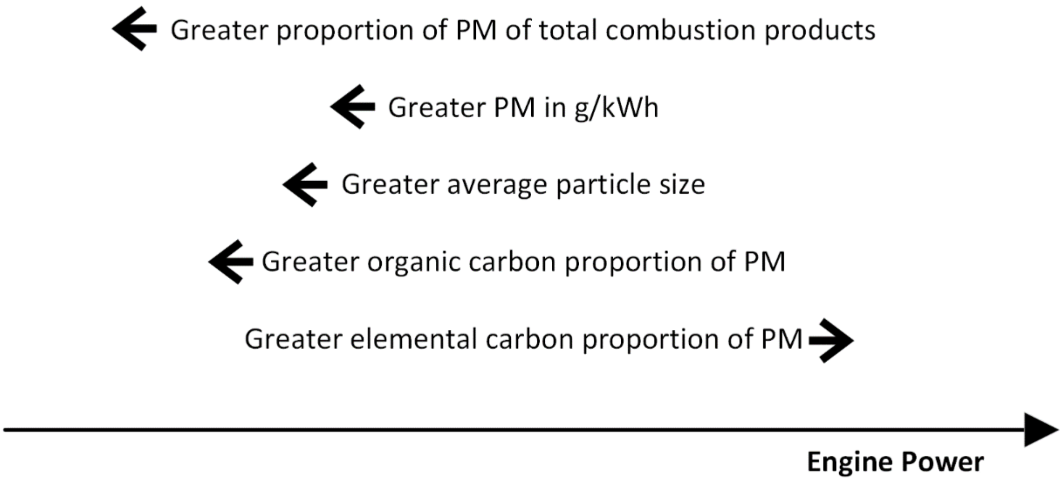
   Reducing the production of PM or PM leaving the cylinder in the first place then reduces the need for abatement and enables the size and cost of abatement equipment to reduced. An engine manufacturer's goal has often been to reduce DPF size to that of a silencer if other methods have been used first.

   A DPF of the types used on rail diesel engines removes PM by directing the exhaust gas through the so-called filter substrate, a fine pore ceramic structure with porous walls inside the filter. PM is deposited on the walls of the channels as the exhaust gas passes through the structure. Most of the time the exhaust temperatures are sufficiently high to continuously burn off the EC PM in the DPF. With cold ambient temperatures or uninterrupted operation under low load, the exhaust temperature can be too low to achieve this regeneration and the engine can be set up to temporarily increase the exhaust temperature to burn off the PM. The measures employed to raise the exhaust temperature may include the reduction of the air-to-fuel ratio, a delayed start of fuel injection, a very late second injection or injecting fuel directly into the exhaust system.

Without DOC also fitted for abatement, the minimum exhaust operation temperature for DPF regeneration using oxygen as the oxidiser is ~400°C. With DOC fitted which converts NO to NO_2 to act as an oxidiser, the extra NO_2 created allows the threshold temperature to drop to ~260°C. The NO_2 is converted back to NO in the DPF as the PM are burnt. As with all abatement technologies the exhaust system back pressure is increased, potentially resulting in a decrease in engine efficiency and potentially increasing in fuel consumption unless the design of turbo is altered.

Reducing the production of PM in turn reduces the need for abatement and enables the size and cost of abatement equipment to be reduced. Figure 9 shows the relationship between engine operating power and characteristics of combustion PM.

Figure 9 Relationship between rail engine operating power and key PM metrics



As regards the GB rail industry:

- Older engines typically have PM emissions (as a % of total combustion emissions by mass) of up to 0.35% at idle and low power and below 0.06% at medium and high-power conditions.
- Newer engines with DOC and DPF will typically have PM emissions (as a % of total combustion emissions by mass) of up to 0.01% at idle and low power, below 0.005% at medium power conditions and below 0.002% high power conditions.

2.6 Hydrocarbons (HC)

Hydrocarbons, or more appropriately organic carbon, emissions arise as a consequence of incomplete combustion of the diesel fuel (as well as a minute amount of engine lubricating oil). Engine exhaust gases contain a wide variety of hydrocarbon compounds that fall into five main categories:

- Paraffins
- Alkenes (olefins)
- Alkynes (e.g. acetylene)
- Aldehydes
- Aromatics

The varied chemical nature of the compounds means there is significant variation in their impacts upon human health and the formation of other secondary AQPs (e.g. through photochemical reactions). The most problematic are volatile organic compounds (VOCs) and oxygenates (which have increased significantly with the use of biofuels).

HC are formed as a result of incomplete combustion with three main factors responsible:

- Insufficient oxygen (including localised effects within the cylinder)
- The presence of carbon-containing compounds that are harder to combust
- Interactions with surfaces or lubricating oils resulting in temperature dropping below levels needed for combustion

Although there are many complex interlinked underlying factors, HC formation, like CO formation (Section 2.3), is relatively well understood. This has allowed solutions to reduce HC (and CO) emissions to be easily implemented on engines. There have been three main routes to reducing HC emissions:

1. Ensuring more complete combustion occurs initially within the cylinder, for example through the use of better turbochargers (to increase oxygen levels) and improved fuel injection technology (to enable better distribution of fuel in the cylinder and faster better-timed fuel injection).

2. The use of DOC abatement technology (in the exhaust system), which can substantially reduce emissions of most types of remaining hydrocarbons or reduce their impact. DOC is covered in detail in Section 2.3. In the hydrocarbon case DOC works by burning (fully or partially) the remaining hydrocarbons (producing CO_2 and H_2O in the fully combusted case).

3. Improvements in fuel quality, for example reducing the levels of certain compounds in the fuel that do not combust well, such as polycyclic aromatic hydrocarbons (PAH).

Hydrocarbon emission levels are typically very similar (+/-15%) to PM levels (in g/kWh) in most engine operating conditions except idle where they are typically double the PM levels.

While included in current emission standards, the challenges of lowering hydrocarbons started to be met in practice 25 years ago or earlier, resulting in minimum reductions of 85% since the 1990s. HC emissions have been reduced as a function of engine changes to reduce other emissions (e.g. of NO_x, PM or CO) or as a result of fuel specification changes (which reduced aromatic content). Hence those hydrocarbons emission are no longer seen as needing prioritising for any further action, with indirect improvement coming as a consequence of actions focusing on reducing other AQPs. These significant reductions in hydrocarbon emissions have been achieved with virtually no impact on fuel consumption.

2.7 Nitrous oxide (N_2O)

While CO_2 is the primary GHG and thus decarbonisation is often treated as synonymous with reducing CO_2 emissions and thus a sector's impact on climate change, other GHGs have a higher global warming potential (GWP). For instance, nitrous oxide (N_2O, which is not an air pollutant and so not recorded as part of NO_X measurements or estimates) has a GWP that is 298 times that of CO_2 over a 100-year time horizon and should be fully accounted for when determining CO_2-equivalent emissions. Therefore, reductions in N_2O emissions (of which small amounts are produced in combustion at elevated temperatures and pressures) should also be addressed as well as emissions of CO_2 when considering decarbonisation. Since generation of N_2O emissions is not linearly related to fuel consumption, a more detailed and granular picture is needed. Calculations based on the latest US EPA data[31] (measurements at a range of power outputs) and Railway Association of Canada data[32] (just measurements in idle) imply that up to 40% of the total GWP from diesel rail freight could be due to N_2O emissions. However, current UK estimates are based on very crude European estimates from the 2019 EMEP/EEA Air Pollutant Emission Inventory Guidebook[33]. This is an aspect that should be considered in future work as it is not covered in this report.

2.8 Production of key air quality pollutants is not linearly related to power output

Emissions of NO_x and PM have similar trends across the range of engine operating conditions, hence there is a very high degree of correlation between low NO_x/low PM conditions and high NO_x/high PM conditions. For instance, NO_x and PM both have the highest intensity of generation in idle as a function of power output, i.e. engine notch (for example see Figure 10), although NO_x intensity of generation is about 10 times that for PM. The resulting concentrations of NO_x from idling trains in key areas such as

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[31] US EPA (2016). *Greenhouse Gas Inventory Guidance - Direct emissions from mobile combustion sources*. EPA Center for Corporate Climate Leadership.

[32] Railway Association of Canada (2013). *Locomotive Emissions Monitoring Program 2013*.

[33] https://www.eea.europa.eu//publications/emep-eea-guidebook-2019

enclosed stations can be above legal limits, while measured PM concentrations are less likely to be above legal limits in such locations. As such, NO_x is the main GB rail emissions challenge, but many learnings are also applicable to PM. Although the underlying formation mechanisms are different, most of the engine conditions that lead to greater intensity of generation of both pollutants are the same. While the intensity of NO_x (or PM) generation as a function of power output is highest at lower engine power outputs (as shown in Figure 10), the total NO_x produced per unit time is highest at higher power outputs as shown in Figure 11 (with the NO_x emission rates in kg/hr).

Figure 10 EMD emissions certification test data for NO_x emissions in g/kWh for the 710 V12 Euro IIIA specification engine (as used in the last 29 Class 66 locomotives ordered by GBRf)

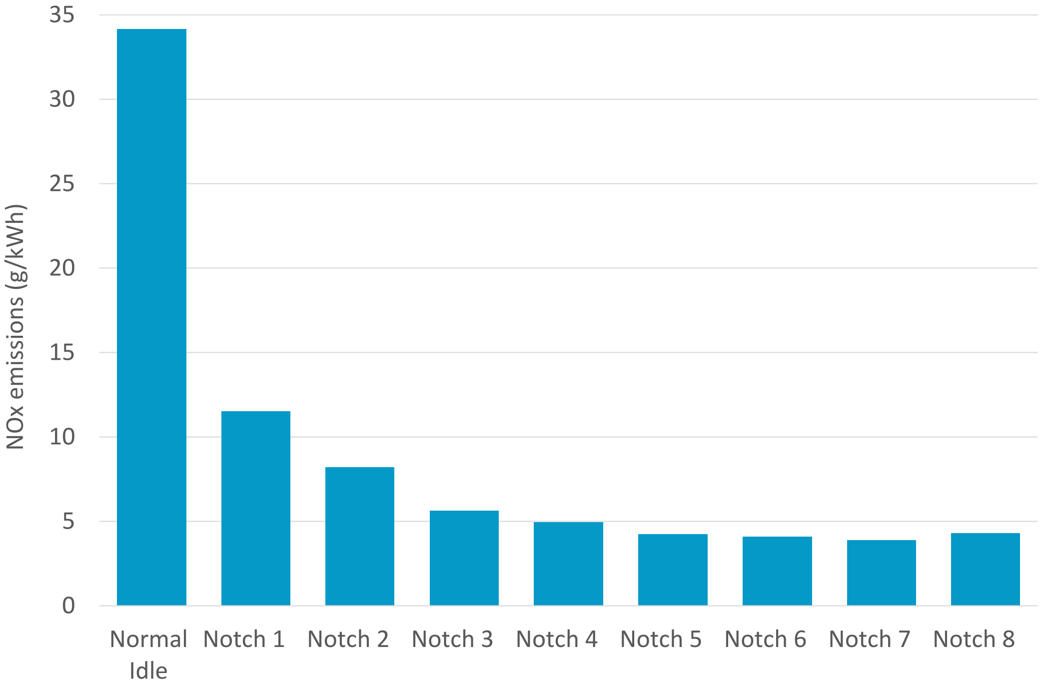
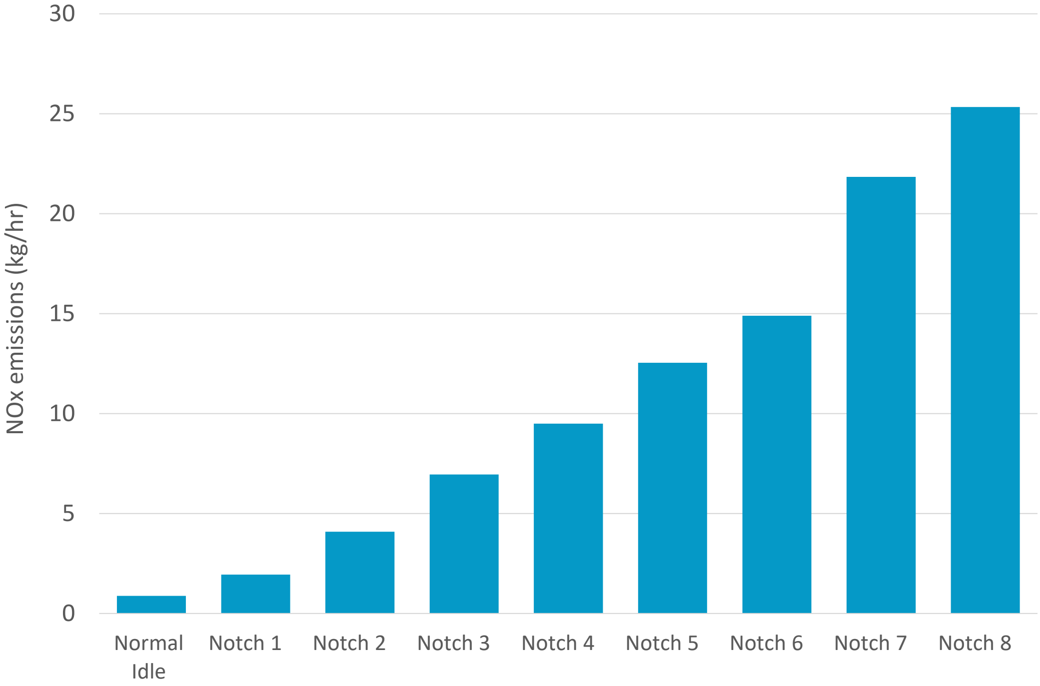
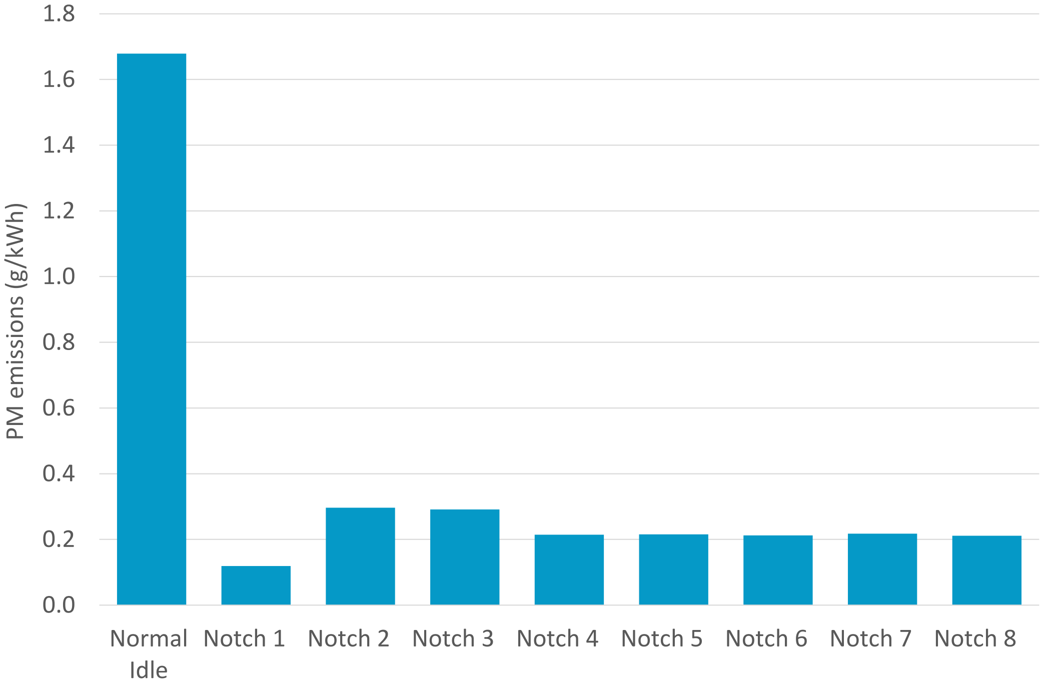


Figure 11 NO$_x$ emissions in kg/hour for the EMD 710 V12 Euro IIIA specification engine



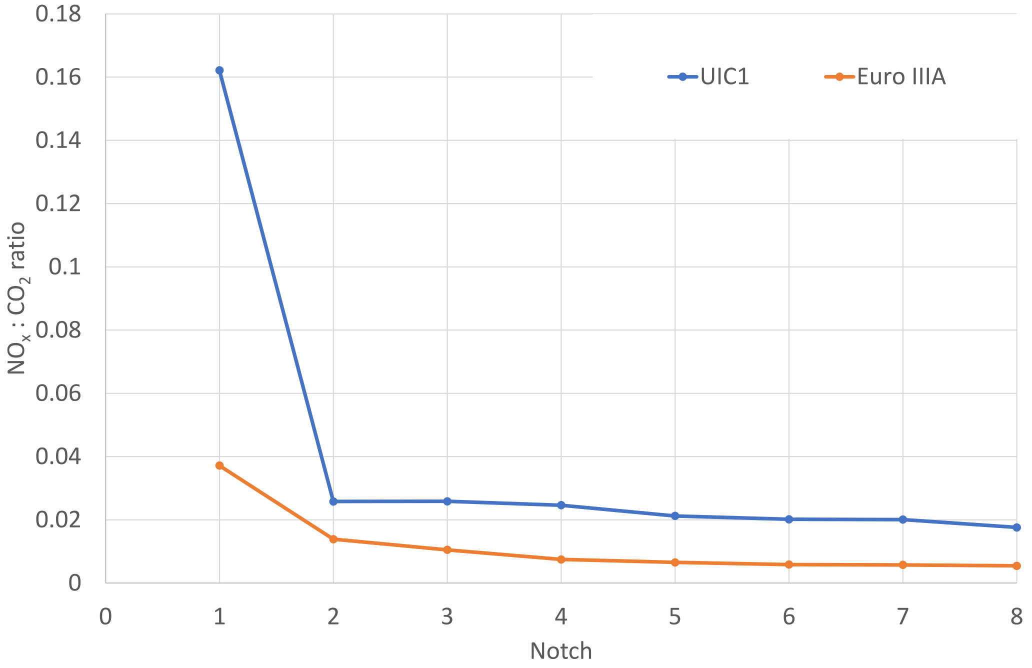
If emissions of NO$_x$ were proportional to engine power then all the bars in Figure 10 would be the same height. In the NO$_x$, PM, CO and HC sections above the relative abundance of AQPs produced (as a proportion of total combustion products or total fuel carbon content) at different engine conditions is briefly discussed to put the various emissions into context. PM, CO and HC all show similar patterns to the NO$_x$ example in Figure 10 above. For instance, the comparable PM (g/kWh) example in Figure 12 also shows higher emissions per unit energy in lower engine power conditions.

Figure 12 EMD emissions certification test data for PM emissions in g/kWh for the 710 V12 Euro IIIA specification engine



In Figure 13 the NO_x emissions as a proportion of CO_2 emissions by notch is shown for both an original UIC-compliant engine and a Euro IIIA-compliant engine. Both curves follow the same pattern as the g/kWh example in Figure 10 . The key message is that the proportion of NO_x, PM, CO and HC of the total combustion products increases at lower engine power outputs.

Figure 13 NO$_x$ to CO$_2$ emissions ratio by engine notch for different Class 66 emission variants



2.9 The importance of idle emissions

At least 75% of engine idle time across the GB rail fleet occurs while the trains are stationary, and furthermore, idle accounts for a minimum of at least half the total engine operating time for most GB train fleets. Emissions produced when stationary are less dispersed which can be expected to lead to higher local pollutant concentrations than when trains are moving at faster than walking pace, even if operating at maximum power.

To understand the impact of NO$_X$ emissions in different engine notches on local air quality, limited dispersion modelling was undertaken for this project. The results in Figure 14 show that NO$_X$ concentrations measured at a single location (a scenario that is equivalent to monitoring with fixed measuring equipment) are heavily dependent on train speed. In this example the Euro IIIA NO$_X$ emission factors from US testing shown in Figure 10 above have been used. At higher speeds emissions are quickly diluted, whereas at emissions produced when stationary in idle are not dispersed and local concentrations can quickly rise, exacerbated by increased NO$_X$ production per unit power output in idle. The standard Department for Environment, Food and Rural Affairs (Defra) guidelines[34] for modelling small generators and combined heat and power (CHP) plant with power outputs equivalent to DMU and locomotive engines have been used to assess concentrations for a single source at the recommended 30 m in this example. While the local effects of NO$_X$ extend wider to a wider range typically 150 m (albeit at

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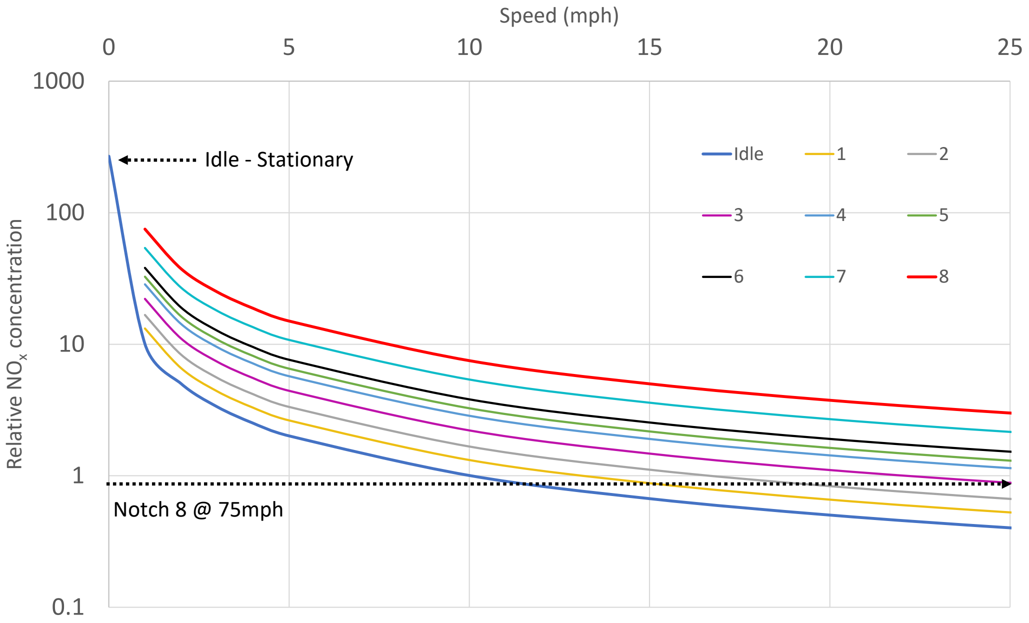
[34] https://uk-air.defra.gov.uk/library/assets/documents/reports/aqeg/chapter5.pdf

lower concentrations) this would be more relevant to aggregating the effects of multiple trains, however the highest concentrations from individual engines are expected within the 30 m. In Figure 14 the modelled relative NO_x concentrations for each notch are plotted from 0 to 25 mph and a logarithmic scale used to display relative concentration. The chosen comparison point for relative concentration (relative concentration = 1) is Notch 8 at 75 mph (full power and speed) which is shown on the graph as the dotted black line. While at a given same speed the modelled NO_x concentrations increase with increasing notch as expected, what is much more significant is the role of train speed, particularly at low speeds. The modelled relative NO_x concentration at stationary and idle is over 400 times the concentration at Notch 8 at 75 mph, with significantly elevated concentrations at walking pacing and below in all notches. This is a simple example and does not account for background levels or multiple trains.

Figure 14 Comparison of relative NO_x concentrations versus speed and notch for EMD 710 engine (Class 66)



While the results in Figure 14 are for a Class 66 freight locomotive, the fundamental implications will not change for other engines used in passenger trains. Idling and accelerating hard away from stationary at low speeds are likely to be of most importance for air quality issues in urban areas in locations such as stations, key junctions, typical holding locations, and freight terminals with large amounts of shunting. Importantly, enclosed stations with limited ventilation further limits dispersion making these situations the highest concern for local air quality impacts.

Specific examples of air quality issues at enclosed stations include the University of Birmingham's work[35] at Birmingham New Street and RSSB's T1122 project[36] addressing air quality at Edinburgh Waverley and London Kings Cross where high measured NO_x concentrations could be correlated with the presence of certain types of rolling type that were idling while stationary near the measuring equipment. Studies[37] away from stations have shown significantly below average expected concentrations in locations where trains are travelling at speed away from stations based on average g/km emission factors that cover a complete drive cycle.

These findings align with the UIC emission studies work from 2004-06[38, 39] where Deutsche Bahn emissions measurement data and modelling from Germany suggested that NO_2 would be almost impossible to measure against the background concentration levels when trains were operating at speed due to dispersal and dilution effects. The study also suggested that NO_2 levels would be worse in busy enclosed terminal stations where trains are idling for substantial periods (Figure 15). This conclusion takes into account the effect of multiple trains at busy or average terminal stations resulting in NO_2 concentrations ~40 times higher than the respective concentration for busy or average lines.

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[35] Hickman, A., C. Baker, X. Cai, J. Delgado-Saborit, and J. Thornes (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): 1864-1878.

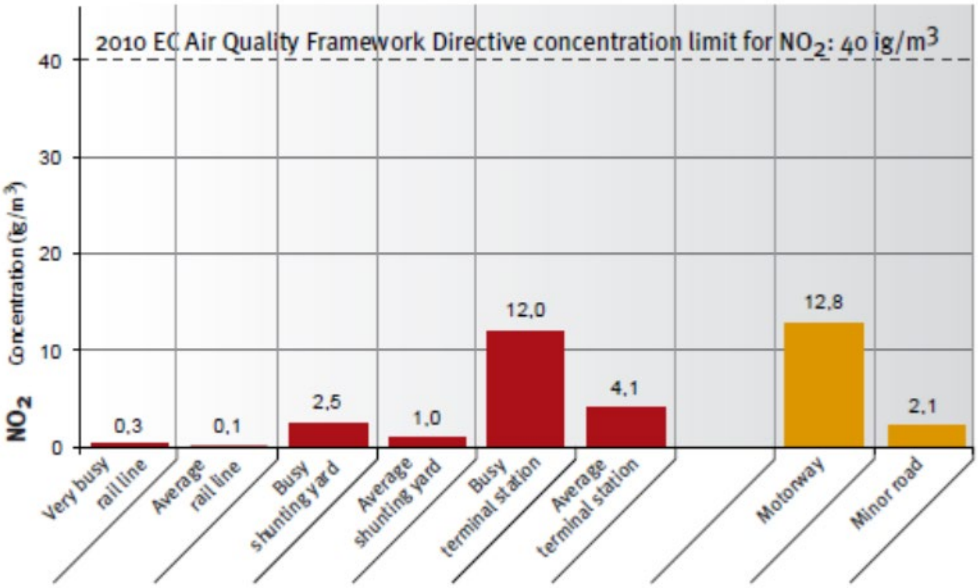
[36] Green, D.C., A. Font, A. Tremper, M. Priestman, D. Marsh, S. Lim, B. Barratt, M. Heal, C. Lin, J. Saunders and D. Pocock (2019). *T1122: Research into air quality in enclosed railway stations*. RSSB.

[37] For example, see Fuller, G., T. Baker, A. Tremper, D. Green, A. Font, M. Priestman, D. Carslaw, D. Dajnak, and S. Beevers (2014). *Air pollution emissions from diesel trains in London*. Environmental Research Group, King's College London.

[38] UIC (2006). *Rail diesel emissions – Facts and challenges.*

[39] UIC (2005-2006). *Rail Diesel Study Work Packages 1-4 Final Reports*. Available at https://uic.org/spip.php?action=telecharger&arg=206

Figure 15 NO_2 concentration in micrograms/m^3 (ig is the German abbreviation for micrograms and ',' is used as the decimal place character) for different typical locations based on Deutsche Bahn's work for the 2004-06 UIC rail diesel emissions study



3 Relevant emission standards

When considering emission factors, an understanding of the emission standards relevant to that particular locomotive or train class is helpful as it will inform what technologies may have been deployed to reduce production of pollutants. An understanding of engine emission standards is also needed to evaluate the difference between real world engine use (and hence real world emissions) and what is needed for an engine to meet an emission standard, and then to evaluate whether the emission reduction technologies used to meet regulatory standard testing are effective in the real world. Most rail diesel locomotive and multiple units have fixed pre-set throttle levels that correspond to fixed power outputs for the engine, thus fixed power/notch factors measured in g/kWh (or g/bhp.hr in US units), i.e. emissions per unit power are based on the physical operation of the engine. Engine control with fixed throttle notches is used extensively in the rail sector globally as well as in the UK.

3.1 Rationale of emission standards

Internationally, across many sectors (including rail), internal combustion engine emission testing and emissions standards are set in units of g/kWh for a given drive cycle. This metric describes the mass of a particular exhaust product that is generated per unit of energy produced (measured at the engine shaft) under a range of operating conditions with the results then weighted according to the given drive cycle to produce a single emission number. The main exception to this metric is the recent introduction of Particle Number (PN) as a second metric for particulate emissions which measures the number of particulates per unit energy (number of particles per kWh). Such single metrics are used by regulators as a simple way to deal with different engines from the same or different manufacturers, encapsulating a range of conditions. However, as will be shown below, this approach belies the complexity of emissions from different operating conditions and masks the importance of emissions in idle which are particularly pertinent to current GB rail industry air quality issues in enclosed stations.

The single metric is derived from a weighted drive cycle of individual test points at different engine operating conditions (e.g. idle, full throttle at maximum engine speed, and some intermediate conditions). It is important to note that for all sectors both the weighting and the test points may not accurately reflect real operating conditions.

In Europe a general principle of emissions regulation is to reduce the total quantity of pollutant emitted in the most effective manner. The overall reduction could be achieved by reducing emissions just for certain engine operating conditions for some or all of the test points (e.g., full throttle, idle, maximum torque) that make up the regulatory drive cycle. Compliance with the single figure emission standard does not mean that emissions will be uniformly reduced across all engine operating conditions. Thus, a halving of the single figure emission standard does not necessarily equate to a straightforward halving of all emissions of the particular pollutant for all engine operating conditions.

It is therefore important to understand how these test cycles are defined and how different test points, representing different modes of engine operation, are weighted.

3.2 Defining emission standards test cycles

For current European non-road mobile machinery (NRMM) emission standards (which apply to rail) and previous European road emission standards, weighting of the regulatory drive cycle to derive a single metric is based on:

$$\frac{\sum mass\ of\ emission\ in\ mode\ a * weighting\ a + mass\ of\ emissions\ in\ mode\ b * weighting\ b + \cdots}{\sum energy\ in\ mode\ a * weighting\ a + energy\ in\ mode\ b * weighting + \cdots}$$

However, this approach mathematically emphasises high power conditions where there is lower intensity of NO_x and PM generation compared to low power (e.g. idle) conditions where there is a higher intensity of NO_x and PM generation per energy produced. This formula averages the grams of emissions produced while skewing the power number in the denominator towards maximum power; essentially the grams of emissions from each individual test point are added and then divided by the total power produced for all test points, thus breaking linkage between the test point results for different engine conditions.

The specific reason for doing the calculation in this way (dating from the 1970s and defined in testing standard BS ISO 3046 (now retired) and later ISO 8178) is that it allowed the use of a single particulate filter for the entire engine test (weighed before and after testing to determine the PM mass) and the much more detailed results (continuous data stream) of the gas testing to be comparable while making testing as simple as possible. Testing technology has advanced considerably since the 1970s hence this is no longer a relevant or justifiable method.

The European heavy duty road emission standard has recently moved to a an unbiased and more appropriate mathematical weighting approach that the US has always used for rail (initially agreed by US EPA, CARB and AAR in 1968) and latterly also for inland marine, which weights individual power notch-based emission factors (in grams per unit power output) according to a drive cycle (based on long term operational data collection):

$$\sum emission\ factor\ mode\ a * weighting\ mode\ a + emisions\ factor\ mode\ b * weighting\ mode\ b + \ldots$$

This method gives a weighting unbiased by the power produced in each mode and hence does not bias in favour of emissions under high power modes and disfavour emissions under low power modes as the previous method did. In the US, where the rail and inland marine sectors are considerably larger and the proportion of total emissions from them is far higher than in Europe, regulation of emissions from NRMM considers specific conditions and locations where there are specific air quality issues. This mathematical weighting approach ultimately requires emission reductions for all parts of the drive cycle, rather than just lowering of emissions for certain (typically higher) power outputs which may be relatively easier to achieve.

As particular emission standards are discussed further in this report, it will be important to be aware of how the particular regulatory test cycles are defined and how these relate to actual engine emissions at different power outputs.

3.3 US rail emission standards

The US has historically led, and continues to lead, in the development and implementation of regulations to address rail emissions. The US started to measure both emissions as well as fuel consumption in the late 1960s as there was a need to understand the origins of air pollutant emissions in order to reduce ambient concentrations. The US initiated measuring rail emissions by different engine notches in 1972 and this was refined through the 1978-1981 NASA study[40] (which included work on drive cycles) becoming the federally mandated measurement methodology in 1984[41].

Though there were initially no regulated US standards, a voluntary agreement was brokered between the US EPA, operators and manufacturers to start reducing emissions on new equipment. California and some other states did, however, start to mandate emission reductions ahead of federal standards. During the 15-year voluntary period, the two US locomotive manufacturers, General Motors Electro-Motive Division (EMD) and General Electric (GE), both adopted electronic fuel injection as standard, and both introduced new engine designs; EMD introduced the 710 engine and GE also introduced the equivalent 7FDL engine. In 1994 the process was started to define an initial set of compulsory standards and test procedures which were adopted in December 1997; along with subsequent amendments for later standards, these are contained in Chapter 40 of the US Code of Federal Regulations (CFR) Parts 85, 89, 92[42] and Parts 1033, 1065 and 1068[43].

Unusually for emission standards, the US rail standards apply not only to newly manufactured engines but also to remanufactured engines, with remanufacturing intervals being mandated via the Useful Life concept. There are both time limits (e.g. 7.5 or 10 years) and total engine use limits (e.g. 10,000 MWh) before an engine requires a full overhaul to an 'as new' state (or in some cases compliant with a newer emission standard that is stricter than when it was manufactured).

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[40] Liddle, S.G., B.B. Bonzo, G.P. Purohit and J.A. Stallkamp (1981). *Future fuels and engines for railroad locomotives: Volume II Technical Document*. NASA-CR-168983, JPL Publication 81-101.

[41] https://www.ecfr.gov/cgi-bin/text-idx?SID=5bbea4132c79edb0269ffc36d2f6ad5c&mc=true&node=pt40.22.89&rgn=div5

[42] https://www.ecfr.gov/cgi-bin/text-idx?SID=d45e5db26491d81997d8b1ced875189d&mc=true&tpl=/ecfrbrowse/Title40/40CIsubchapC.tpl

[43] https://www.ecfr.gov/cgi-bin/text-idx?gp=&SID=63624e55cc6730c15513d62d3b69b53e&mc=true&tpl=/ecfrbrowse/Title40/40CIsubchapU.tpl

The first batch of US standards included three standards known as Tiers 0, 1 and 2 which became progressively stricter and were rolled out over time, initially applying to new locomotives manufactured after the introduction dates and in a more limited way to older engines manufactured from the start of 1973 onwards. The significance of 1973 is that it was the first year after comprehensive testing started after a period of 5 years of concerted work on fuel consumption and emissions, and it was the first year of the current US locomotive market duopoly of GE and EMD (the last remaining competitors going out of business the previous year). Rolling emission standards further back would have been impossible since there was no manufacturer support for non-EMD/GE products and there had been no significant focus in earlier engine designs on fuel consumption or emissions.

The initial focus on emission reductions was on CO and HC, pollutants that both regulators and manufacturers had a good understanding of (e.g. from studies of smog formation in California). Furthermore, these were pollutants for which locomotive manufacturers also had an understanding of how to reduce emissions through actionable engine design improvements that would also improve fuel consumption, e.g. better fuel injection system design, leaner combustion through using larger turbochargers and not using Roots-type blowers (positive displacement superchargers). At the time the understanding of PM and NO_x formation was limited in comparison.

- Tier 0—The first set of standards applies (from January 2000) to locomotives and locomotive engines originally manufactured from January 1973 to December 2001, any time they are manufactured or remanufactured. Electric locomotives, historic steam-powered locomotives, and locomotives originally manufactured before 1973 are exempted from the emission standards.
- Tier 1—These standards apply to locomotives and locomotive engines originally manufactured from 2002 to 2004. These locomotives and locomotive engines are required to meet the Tier 1 standards at the time of the manufacture and at each subsequent remanufacture.
- Tier 2—This set of standards applies to locomotives and locomotive engines originally manufactured in 2005 and later (left open ended till the next set of standards, Tier 3 and 4, were finalised). Tier 2 locomotives and locomotive engines are required to meet the applicable standards at the time of original manufacture and at each subsequent remanufacture.

In March 2008, a second batch of two emission standards know as Tier 3 and 4 were finalised (after a long consultation process with industry and significant disagreement over Tier 4) which have more stringent emission requirements. The 2008 regulations also included more stringent emission standards for remanufactured Tier 0-2 locomotives (known as Tiers 0+, 1+ and 2+) which would require reductions to emissions below those at the respective time of manufacture.

- Tier 3 standards (2012-2014) were designed as an intermediate step to Tier 4 using just in-engine technology.
- Tier 4 standards were originally intended to require mainly the addition of exhaust stream gas aftertreatment technologies, such as diesel particulate filter (DPF), Diesel Oxidation Catalyst (DOC) and selective catalytic reduction (SCR). However, some commercial locomotive engines (from both GE and EMD) were able to meet Tier 4 standards without aftertreatment technologies through the further use of in-engine technologies, e.g. exhaust gas recirculation (EGR). These standards became effective from January 2015 and are not expected to change in the long term.

To enable catalytic after treatment methods at the Tier 4 stage, the US EPA regulated (as part of the broader non-road Tier 4 rules) the required use of low sulphur diesel fuel for locomotive engines. This involved a sulphur limit of 500 ppm from June 2007 and a sulphur limit of 15 ppm from June 2012, with California mandating slightly lower levels (that are the same as European ones). The reduced sulphur levels have also reduced the formation of sulphur-based PM and hence overall PM emissions.

3.4 US drive cycles

Two test cycles are used to weight the steady state in notch test measurements developed from 1971 to 1976 based on real world operations and represent two different types of service typical in the US including line-haul and switch locomotives. The drive cycles include different weighting factors for each of the eight throttle notch modes, which are used to operate locomotive engines at different power levels, as well as for idle. The switch drive cycle involves much time in idle and low power notches, whereas the line-haul operation is characterised by a much higher percentage of time in the higher power notches, especially Notch 8. A dual cycle approach has been adopted in the regulation, i.e., all locomotives are required to comply with both the line-haul and switch duty cycle standards, regardless of intended usage (effectively making the standards stricter by forcing larger improvements at both low and high engine power states than what just a single cycle would have done). The US rail industry and US EPA recognised in the 1970s that real world usage, not idealised usage, should be reflected in the drive cycles and that different patterns of usage would have different typical drive cycles that should be represented with different regulatory drive cycles.

The US locomotive certification and compliance programs include several provisions, including production line testing and in-use compliance emission testing, as well as averaging, banking and trading of emissions. Hence in practice engine emissions need to be a reasonable margin below regulatory thresholds to guarantee that a sufficient number of engines under a variety of conditions would meet the standards to get certified in the US.

The European Commission, Member States and other stakeholders in Europe have only recently started to use or think about using some of these concepts in the largest NRMM sectors. They are now discovering that it is far more complex and difficult to effectively include real world drive cycles than had been anticipated (e.g. real world PEMS monitoring of construction equipment is showing that the drive cycle for this sector is similar to rail with a large amount of time in idle). NRMM testing for rail (a relatively small market) is still covered by single engine testing on a test bed approach without production line or in-use testing.

3.5 European rail emission standards

In general, Europe has been behind the US in understanding and regulating combustion emissions, and non-road engine applications have lagged behind road applications. The European approach is somewhat akin to a series of '80:20' approaches at reducing emissions. For example, in Europe around 85% of internal combustion engine fuel is used in road vehicles, hence there was an initial focus on road vehicles a decade before NRMM equipment. The subsequent regulatory focus on NRMM applications has been on just two diesel engine categories (both non-rail) that represent around 75% of total NRMM engine sales in Europe. These categories of engines, NRE-v/c-5 and NRE-v/c-6, are typically fitted to construction equipment with power outputs between 56-130 kW and 130-560 kW, respectively.

The European strategy has been on reducing total volumes of pollutants produced in a cost-effective manner. This has often led to a single technology solution approach in Europe, unlike in the US where reduction technologies deployed may vary by usage sector. For example, the NRE-v/c-5 and NRE-v/c-6 NRMM diesel engine categories have typical drive cycles where SCR will be suitably effective in reducing NO_x emissions in real use. However, for some other NRMM sectors including rail, SCR will be less effective given their different drive cycles.

In Europe, at government and regulatory levels, rail and larger inland marine engines were viewed as global market products, with the number of engines sold being comparatively low compared to other NRMM sectors. Hence only small overall emissions reductions could be achieved through their regulation and therefore they were not included in the original NRMM regulations in Directive 97/68/EC[44] (which were developed in the mid-1990s in parallel to the US Tier 0-2 non-road standards) that only applied to engines of less than 560 kW. (Note that this rating is smaller than all locomotive engines and some larger underfloor DMU engines.) Consequently, the rail industry was originally self-regulated with the Union International des Chemin-de-Fer (UIC) creating emission standards, which were mandatory in some countries and voluntary in others (such as the UK, which has led to the view that there were no UK rail emissions rules at that time). The UIC in Europe (and beyond) achieved weaker and later-starting voluntary agreements before compulsory regulation than the US, Canada and New South Wales, Australia.

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[44] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31997L0068

The first two UIC standards, known as UIC1 (see UIC Leaflet 623[45] from 1992) and UIC2 (see UIC Leaflet 624[46] from 2001), aimed to try to combine elements of the US Rail Tiers 0-2 and European NRMM Stage I and II to create a trajectory on emissions reduction over time while taking account of rail-specific requirements such as restricted space, dimensions and comparatively very long working lives of engines.

Emission testing and certification in Europe has lagged behind the US until quite recently as rail diesel use was falling due to electrification programmes in Europe, thus reducing the pressure to monitor emissions. Emission testing in Europe is carried out differently from the US, with the original drive cycle for rail testing developed by Deutsch Bundesbahn (DB) engineers for the Union Internationale des Chemins de Fer (UIC) to be included in a standard that was then being developed for testing Non-Road Mobile Machinery (NRMM) engines. That standard evolved to become ISO 8178 with the 'locomotive' test cycle becoming the 'F' test cycle that has remained unchanged since 1982. The ISO 8178:F drive cycle is based on estimated use patterns of a single design of DB Diesel locomotive with hydraulic transmission in 1977 on both freight and passenger use. This locomotive had served as the design template for the British Rail Western Region Class 52 diesel hydraulic locomotives), a reasonable but not perfect choice of drive cycle for Great Britain.

Many European countries undertook significant electrification schemes in the 1980s and combined with comparatively little diesel rolling stock being replaced this led to low demand for rail diesel engines in the 1980s. However, UIC recognised this demand for engines was a cyclical low point in the market. A renewed focus on air quality in the late 1980s combined with an expected upturn in the rail diesel engine market led to the first UIC (largely European) emission standard known as UIC1. This was published in 1992 (as UIC Leaflet 623 now known as IRS 60623[47] from late 2019) and came into effect in 1993 but was less strict than the equivalent stage/tier of US standards (when drive cycle, mathematical weighting and testing requirements are taken into account). The slightly stricter UIC2 (but still not quite as strict as the US equivalent when taking differences into account) came into effect at the start of 2003.

The thinking informing UIC emission standards had a similar focus to that for both US rail emission standards and early (pre-rail inclusion) European NRMM emission standards. This was on tackling easier and/or cheaper to address emissions in earlier standards while leaving the significant reductions in the more difficult and expensive to address NO_x emissions (as well as an additional tranche of PM reduction) until later standards.

The UIC had already developed the draft for their next standard (UIC3) when the EU decided to bring rail (and inland marine) into the NRMM rules when amending Directive 97/68/EC in 2004 (one of five amendments in total before this directive was replaced in

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[45] https://www.shop-etf.com/en/certification-procedures-for-diesel-engines-of-motive-power-units
[46] https://www.shop-etf.com/en/exhaust-emission-tests-for-diesel-traction-engines
[47] https://www.shop-etf.com/en/certification-procedures-for-diesel-engines-of-motive-power-units

2016). Consequently, the EU effectively directly adopted UIC3 as NRMM Rail Stage IIIA (only a single digit was changed for just one pollutant standard). This standard was introduced between 2006 and 2009 depending on the engine size and application (locomotive or DMU) with some technical details not included in either the NRMM engine regulations or ISO 8178:F covered by UIC Leaflet 624 (now IRS60624[48] from late 2019).

Euro IIIA is broadly equivalent to the US Tier 2 standard (when differences between European and US drive cycles and weighting are taken into account), with several manufacturers being able to supply engines of a single design that complied with both European and US standards rather than having differing design variants for the two markets.

Rail Stage IIIB, the first rail standard developed by the European Commission (as another amendment to 97/68/EC), was effectively delayed in introduction from 2012 to 2015 in that existing engine designs already in use were given an extra three years to comply. The European NRMM standards have always had different implementation dates for different sectors or applications. Sectors with high engine sales volume are at the beginning of the implementation date range while sectors (including rail) with lower sales volume are at the end implementation date range. The aim is to implement change in the high-volume sectors first as this will result in larger emission reductions sooner. The staggered implementation dates are often not well communicated by the European Commission (who focus on the earlier dates for high sales volume sectors) and therefore often not widely understood by rail industry stakeholders.

The stricter Euro IIIB standard had a delayed introduction in 2015 and is similar to US Tier 3 (after adjusting for different US and European drive cycles and mathematical weighting approaches) but also saw a change of drive cycle from the ISO 8178:F drive cycle to the NRMM standard default ISO 8178:C1 drive cycle (Table 1). The weightings for the C1 test cycle (for IIIB) are not representative of rail engine usage (for example just 15% of time at idle). The low weighting for idle (where emissions on a g/kWh basis are highest) means it is easier to comply with IIIB with the C1 test cycle than if the F test cycle had been retained. Note that in Table 1 Test Modes 1, 6 and 11 are the most relevant for diesel rail use with traditional type electric transmission. Test Modes 1-3, 8 and 11 are the most relevant for diesel rail use with more modern (3-phase drive) electric transmission and sophisticated engine management computers (Test Mode 9 would also be useful since it mirrors real rail engine set-ups, but it is not part of the C1 or F test cycles). For diesel hydraulic and diesel mechanical transmissions the data from all the test points is relevant (including the unweighted and untested Test Modes 4, 9 and 10).

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[48] https://www.shop-etf.com/en/exhaust-emission-tests-for-diesel-traction-engines

Table 1 ISO 8178 C1 and F drive cycle mode weighting table

Speed	**Rated speed**					**Intermediate speed**					**Low Idle**
Test Mode number	1	2	3	4	5	6	7	8	9	10	11
Torque, %	100	75	50	25	10	100	75	50	25	10	0
C1	15%	15%	15%	-	10%	10%	10%	10%	-	-	15%
F	25%	-	-	-	-	-	-	15%	-	-	60%

NRMM Stage IV does not exist since Stage IIIB was an intermediate step for rail before Stage V which becomes effective for rail at the start of 2021. The only real difference between the current Stage IIIB and the future Stage V is the introduction of a particle number (PN) standard for railcars but not for locomotives. The only practical design change for Stage V (defined by the new NRMM directive 2016/1628/EU[49]) being abatement systems (rather than any engine changes), requiring revised design and/or increased size of DPFs, and on some engines an increased size of DOC fitted (depending on the mixture of particulate origins e.g. if unburnt HCs including lubricant oil need to be reduced). These requirements also potentially make it more difficult to find space for abatement systems on last-mile type diesel locomotives in particular.

Both the US and Europe regulatory regimes encourage the retrofit concept where older locomotives can be upgraded to comply with newer engine emission standards with new engines or parts and equipment, but not necessarily to the comply with the latest emission standards. The overall aim is to maximise emissions reduction which can often be best achieved with reasonably-sized emissions reductions for a greater amount of older rolling stock, rather than minimising the emissions on a far smaller number of new current emission standard-compliant rolling stock for the same cost, provided there is a reasonable working life left in the older rolling stock.

Unlike US rail emission regulations, there are no formal European mandates to upgrade existing rolling stock over time. Thus, existing rolling stock can be re-engined with new engines legitimately manufactured to a lower than current emission standard for new engines or rolling stock (rather than just upgrades to existing engines), if it is practically impossible or not economically viable to meet the more stringent requirements. This is primarily on the basis that emissions are (substantially) reduced beyond a do-nothing case with the secondary reasoning that the best benefit to cost ratio (BCR) of emission reduction often comes from re-engining a larger number of existing locomotives than

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[49] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R1628&from=EN

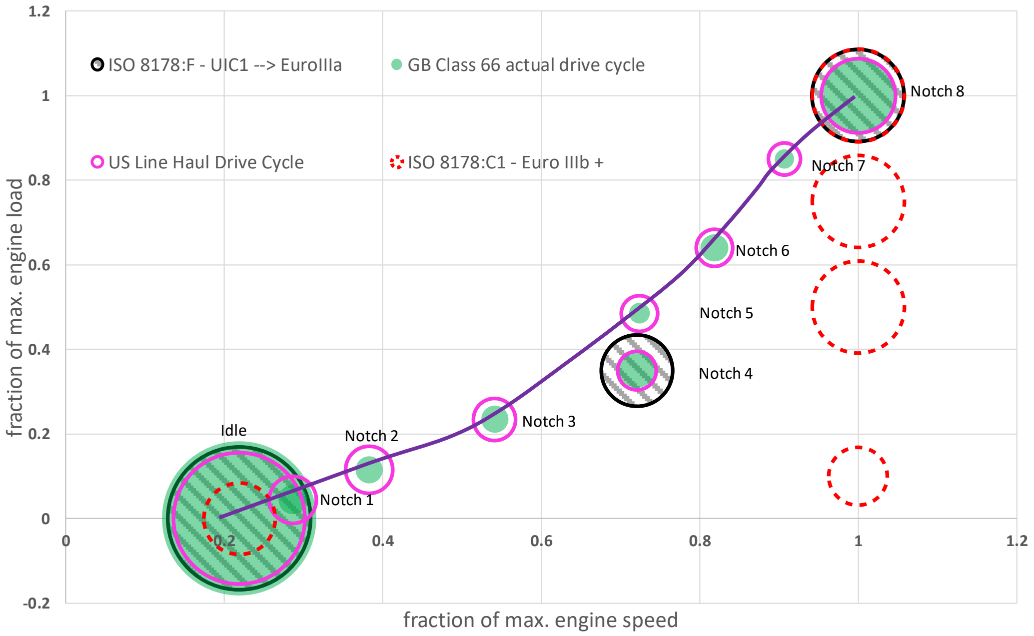
purchasing a far smaller number of new locomotives for the same cost, provided there is a reasonable working life left.

An example of this is the retro fitting programme being undertaken for GBRf by EMD of a number of Class 56 freight locomotives. These locomotives are currently with engines that are pre-certification era (a 1970s version of an older engine design) and are being retrofitted with new EMD 710 engines. These engines are Euro IIIA compliant rather the current Euro IIIB standard for new rolling stock. However, they still offer substantial reduction in emissions and are therefore appropriate in the context of overall emission reduction, given both the additional cost and lack of space for SCR and DPF equipment in an older locomotive design. Recent other GB examples include the HST fleet and some Class 73 locomotives. Another advantage of using an engine compliant with a slightly older emission standard is that its reliability is fully understood, unlike engines that are compliant with current emission standards but which have yet to be used in service.

3.6 Comparing US and European rail emission standards

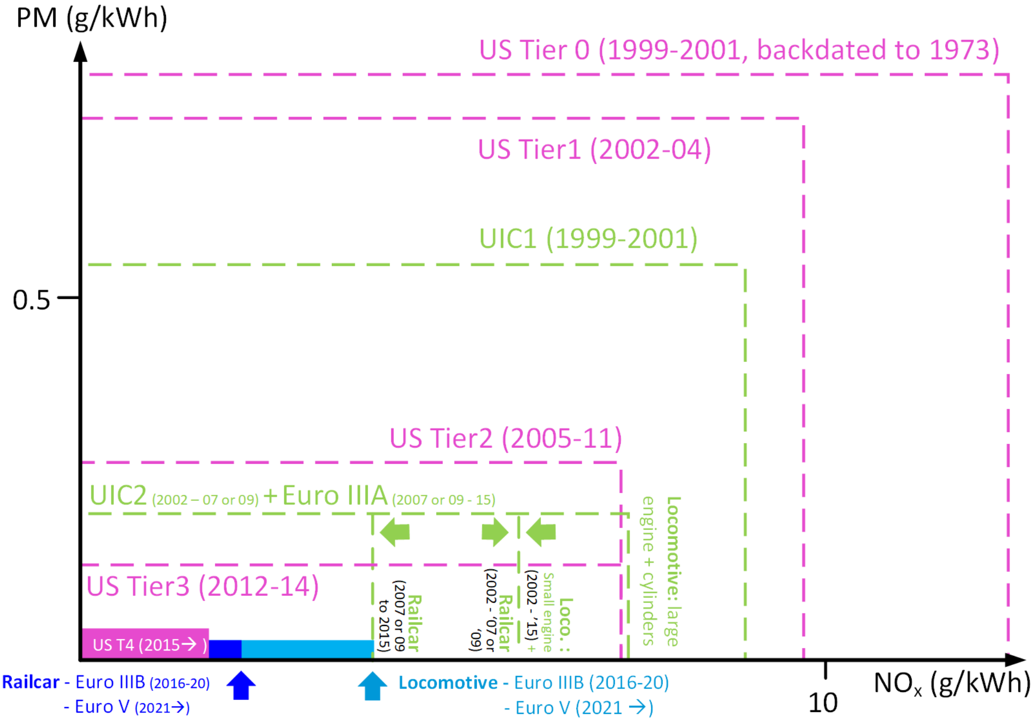
There are key differences between the US and European regulatory rail drive cycles which should be considered before comparing the respective rail emission standards. In Figure 16 below the real GB freight drive cycle is compared with both the European drive cycles and the US line haul drive cycle. Note the bias in the weightings for the ISO 8178:C1 cycle to higher power/throttle conditions where emission factors in g/kWh are lower and which do not align with real engine operating conditions, as well as having a low weighting for idle.

Figure 16 Comparison of Class 66 actual drive cycle with the individual mode weightings used to create the aggregated factors for European and US rail emission standards



The evolution of US and European rail emission standards for NO_x and PM is shown in Figure 17 . It should however be noted that the US test drive cycle and mathematical weighting is different to the both earlier (Euro IIIA and earlier) and later (Euro IIIB and V) European ones so these three groups of test cycles (US, ISO8178:F and ISO8178:C1) are not directly comparable. The earlier European standards and the equivalent US standards tend to align much more closely based on detailed analysis of real engine emission test data and accounting for the effects of different drive cycles and mathematical weightings. More importantly, the Euro IIIB/V reductions shown in Figure 17 are not anywhere near as large as might be expected given the change from F to C1 drive cycle and the substantial reduction in weighting of emissions at idle.

Figure 17	Evolution of European and US rail emission standards for NO_x and PM



The difference between US and ISO drive cycles will typically result in a difference in the aggregate emission factors that are ~10% higher for NO_X and ~25% higher for PM for the same engine just by changing from US to ISO 8178:F drive cycle weightings, with even greater differences for US vs ISO 8178:C1 drive cycles due to the lower idle weighting of the C1 drive cycle. Hence the US and European standards align much more closely than it might at first appear (European standards appear to be lower in comparison before the difference in drive cycle is taken into account).

The rail emission standards limits for each AQP, along with the test drive cycles and dates for Europe and US have been summarised in Table 2 :

Table 2 European and US rail emission standards in g/kWh, except particle number (PN) which is in number of particles per kWh

Standard	Start Year	Actual Year	Drive Cycle	CO	HC	HC + NO_X	NO_X	PM	PN
UIC1	1999		ISO 8178:F	5	1.3	-	9.2	0.54	-
UIC2	2002		ISO 8178:F	3.5	1	-	6	0.2	-
Euro IIIA Railcar	2006		ISO 8178:F	3.5	-	4	-	0.2	-
Euro IIIA Locomotive (*S)	2009		ISO 8178:F	3.5	0.5	-	6	0.2	-
Euro IIIA Locomotive (*L)	2009		ISO 8178:F	3.5	0.4	-	7.4	0.2	-
Euro IIIB Railcar	2012	2015	ISO 8178:C1	3.5	0.19	-	2	0.025	-
Euro IIIB Locomotive	2012	2015	ISO 8178:C1	3.5	-	4	-	0.025	-
Euro V Railcar	2021		ISO 8178:C1	3.5	0.19		2	0.015	1×10^12
Euro V Locomotive	2021		ISO 8178:C1	3.5		4		0.025	-
US Tier 0	1999 (1973) +		US Line Haul	6.7	1.3	-	12.7	0.80	-
US Tier 1	2002		US Line Haul	3.0	0.7	-	9.9	0.60	-
US Tier 2	2005		US Line Haul	2.0	0.4	-	7.4	0.27	-
US Tier 3	2012		US Line Haul	2.0	0.4	-	7.4	0.13	-
US Tier 4	2015		US Line Haul	2.0	0.2	-	1.7	0.04	-

*L = for engines of P >2000 kW and D >5 litres/cylinder e.g. EMD, GE, CAT in GB rail use

*S = engines of P >2000 kW and D <5 litres/cylinder e.g. MTU4000 in GB rail use

[+] US Tier 0 was retrospectively rolled back to engines manufactured from 1973 onwards

3.7 Rail emission standards drive cycles compared to real GB rail drive cycles

Figure 18 shows engine notch settings in terms of engine speed and load, along with the real GB freight drive cycle (bubble area is proportional to time in a given notch). The coloured background of this figure shows indicative shaded regions of idealised NO_x emission levels[50] (in g/kWh) without exhaust system abatement, with isolines between low NO_x g/kWh (green) and high NO_x g/kWh (dark red) regions. Note that the iso-NO_x lines are intended to show a generalised trend of how NO_x emissions vary across an engine's operating range and may differ from and between actual engine types used in the GB rail industry.

The engine operating conditions for a given notch generally follow the traditional maximum power curve (the purple line in Figure 18) which is the engine control strategy in older diesel electric locomotives. However, in this case (a Class 66) the conditions for Notch 4 have been altered (increased rpm) to reduce engine vibration resonance issues. These changes to engine operating conditions for Notch 4 are reliant on the engine having electronically controlled higher-pressure fuel injection systems and sophisticated computer-controlled engine management. This enables newer engines with electric transmission to run at higher speeds at lower power settings than older engines with electric transmission (which have maximum power curve-based engine control strategies).

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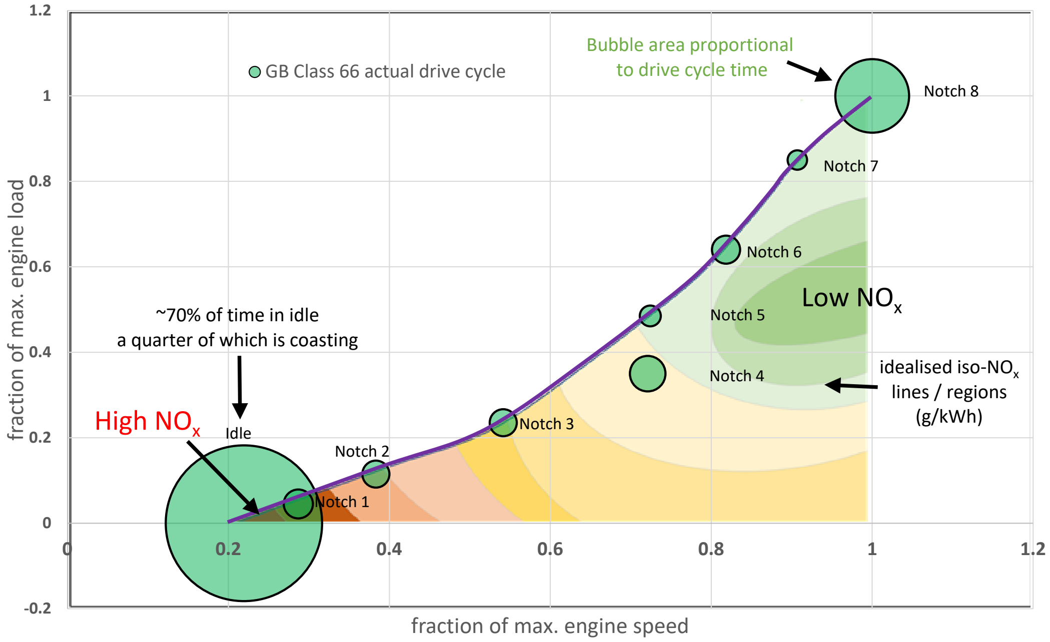
[50] Based on general understanding of full-map engine emissions testing data.

Figure 18 Engine notch setting in terms of engine speed and load, real GB freight drive cycle and indicative regions of idealised NO_x emission levels

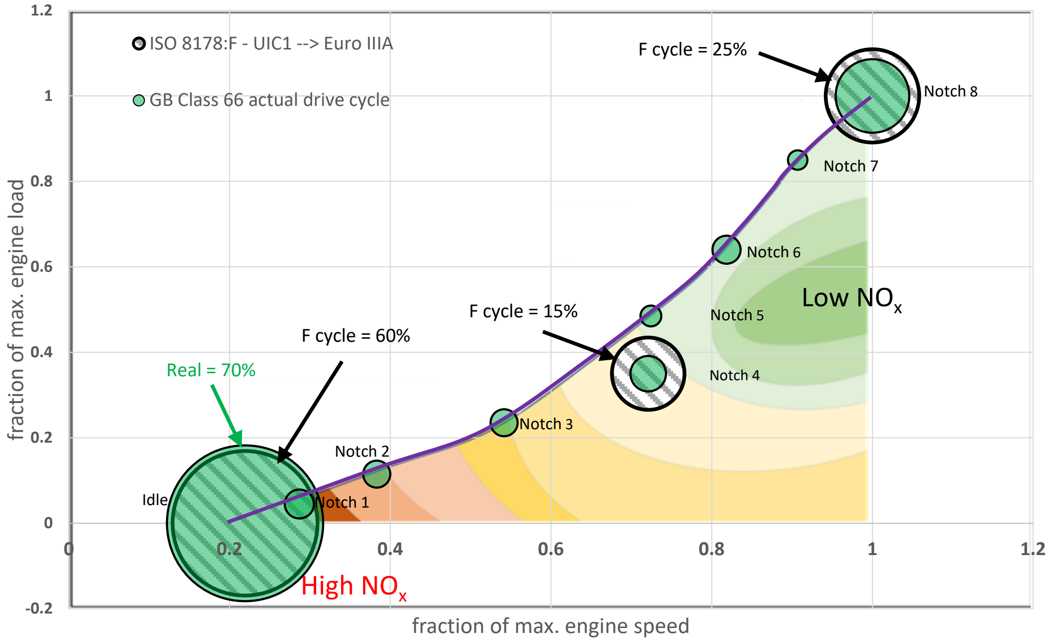


The freight example in Figure 18 has been used in many places in this report as it has the best overall data availability and data quality needed to quantifiably illustrate the themes being discussed throughout the report. The freight drive cycle is also reasonably representative of most GB diesel rolling stock drive cycles, especially the relatively high proportions of idle compared to most other road or NRMM engine drive cycles. For example, typical freight idle is 70%, while for the Sprinter family trains (Classes 150-159) with hydraulic transmissions that are used on many local and regional passenger services the typical time spent idling is 67%. For higher speed passenger trains with electric transmissions (e.g. High Speed Trains and Voyager/Meridian family trains) the time spent idling is slightly lower in the 50-65% range depending on operator, train length, typical routes and stopping patterns.

Rail naturally has more engine idle with all hydraulic and electric (and some mechanical) transmissions permitting coasting due to the lower rolling resistance that is inherent to the physics of rail but not road (or off-road) wheel movement. This allows a train to continue moving for miles with the engine(s) effectively being disconnected from the wheels and the engine(s) effectively just supporting auxiliary loads in idle – equivalent to a road vehicle being in neutral. (Typically, a minimum of 15%, and a maximum of nearly 25% in certain cases, of the total rail drive cycle by time and a minimum of 8% by distance involves coasting or braking.)

As discussed above, the UIC1, UIC2 and Euro IIIA standards shown in Table 1 used the ISO 8178:F drive cycle which, while not perfect in that it under represents idle usage in most rail applications (freight and non-high speed DMUs), is a reasonable approximation as shown in Figure 19 of a real GB freight drive cycle and is closer than most regulatory drive cycles to real drive cycles. The F drive cycle used for Stage IIIA and earlier standards slightly under-represents the proportion of time in idle and has only three test points.

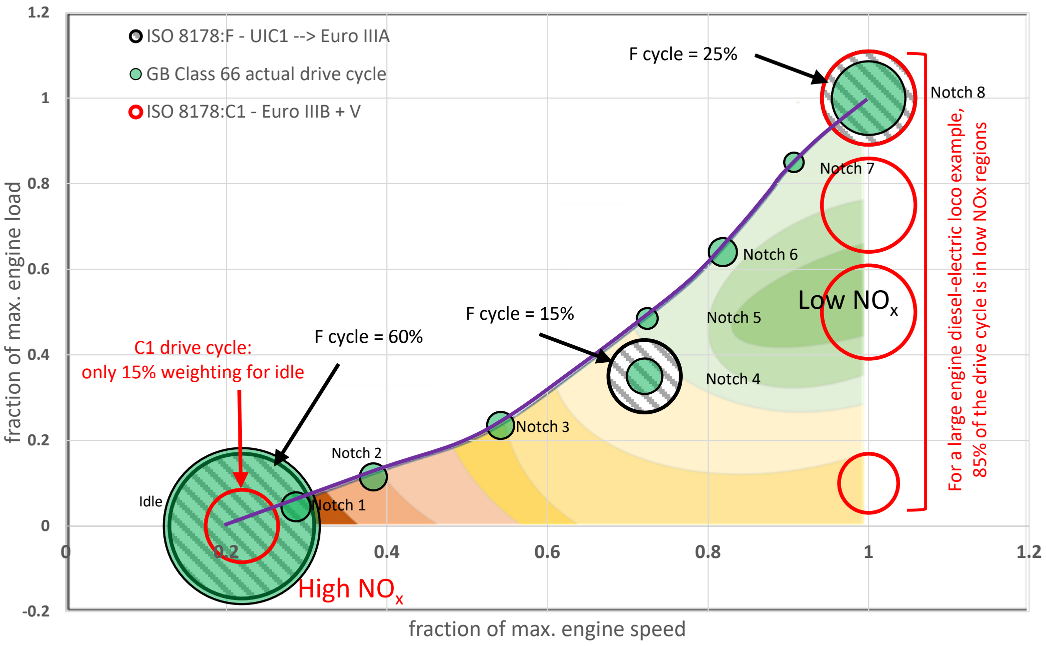
Figure 19 Class 66 engine operating conditions along with real freight and ISO 8178:F drive cycles



The current NRMM Stage IIIB (and future Stage V) emission standards are not well related to real world emissions; IIIB saw the change away from the F cycle to the far less representative C1 cycle. This change in representativeness is a combined consequence of a single metric based on invalid averaging of individual test points and an unrepresentative drive cycle that cumulatively result in a poor representation of actual emissions. Figure 20 shows how different the C1 drive cycle (red circles in Figure 20) is to both the real freight and F drive cycles. The C1 drive cycle is also based on mechanical rather than electrical or hydraulic transmissions in end applications.

In the example in Figure 20 (a large locomotive engine with electric transmission) the maximum engine torque and maximum engine operating speeds, which are both used to define three test points at each speed, are the same. Running any engine for electrical generation purposes any faster than the maximum torque speed is worse for fuel efficiency. Hence three of the test points shown in Figure 20 are actually identical to three others resulting in a very large weighting for high running speed and high engine power conditions. These are also generally low NO_x conditions (see Section 2.4) which mean that the apparent emissions reductions from IIIA to IIIB are not as large as they might appear by just considering values of the standards. The C1 drive cycle in this case is more aligned to portable or back-up electrical generation (which uses ISO 8178:D cycles) and does not include much operation in the low NO_x/PM area. Hence large electric transmission engines are not directly comparable to railcar sized ones and the UIC and later EU therefore have different emission limits for railcar and locomotives. Note that while the Stage IIIB C1 drive cycle and the earlier Stage IIIA F drive cycle both under-represent the proportion in idle, the C1 cycle vastly under-represents the amount of time in idle.

Figure 20 Class 66 engine operating conditions along with real freight, ISO 8178:F and ISO 8178:C1 drive cycles



3.8 Rail emission standards: Implications for understanding and addressing air quality issues

The GB rail industry has been potentially lulled into a false sense of security because GB rail engines comply with a single small emission standard (in g/kWh) which hides behind it much bigger permissible idle emissions (in g/kWh). The current mathematical approach to weighting different parts of the drive cycle means that emissions at full throttle and the energy produced at full throttle dominate the data used to determine compliance with the current standards. Furthermore, emissions generated during idling are a significant part of the enclosed station air quality problem.

However, actual emissions in key locations for certain engine configurations may be significantly higher than would be implied by a single metric. Furthermore, emissions generated during idling combined with limited dispersion are a significant part of the enclosed station air quality problem (see Section 2.9). Rail engine auxiliary loads at idle are also far higher than idle in other sectors, hence idle in the rail context needs to be reflect real rail idle and not just minimal auxiliary loads under testing conditions. All GB trains spend the majority of time in idle, but this is not reflected in the current NRMM Stage IIIB regulatory drive cycle for rail. The change in Idle weighting from 60% to 15% in the drive cycle from Stage IIIA to IIIB also means that the reductions in permitted levels of AQPs between the two stages are far less than it might appear.

The single metric approach to rail emission standards could be improved by using a more valid mathematical weighting approach and a more realistic drive cycle, but to effectively address key rail air quality problems there is a need for an understanding of emissions by notch, i.e. in all engine operating conditions, not just compliance with a single number. Mandating a lower single-number emission standard limit alone without other changes to emission standards and testing will not produce significantly lower idle emissions – which are a significant part of the air quality issue for rail. Following a similar approach to the US that includes published individual data points (by notch), realistic rail drive cycles and appropriate weighting mathematics would allow compliance with a single number to be more meaningful and at the same time provide the GB rail industry with usable data to better aid its understanding of emission issues and potential solutions.

4 Review of previous rail emission factors

The UK National Atmospheric Emissions Inventory (NAEI) is a compilation of estimates annual pollutant emissions from 1970 to the most current publication year for the majority of pollutants emitted from anthropogenic sources in the UK. Prior to the current RSSB work, the emission factors used to estimate rail emissions for the NAEI were the most comprehensive set of available GB rail emission factors. While used to develop national total emissions estimates, these factors have a number of limitations as regards application to local air quality studies. In this section the origin and applicability of the emission factors used in the NAEI until very recently is reviewed and critiqued.

4.1 Coverage

The rail emission factors published on the NAEI website[51] are in units of kt of pollutant per Mt of fuel used. This is consistent with other sectors in which fuel is combusted. However, these factors are not actually used to compile the NAEI rail emissions estimates. In fact, they are back-calculated at the end of the compilation process by dividing estimates of total emissions from the rail sector by the total rail sector fuel usage.

In order to derive estimates of emissions from the rail sector in the UK NAEI, emission factors in grams per locomotive or vehicle-km for the major locomotive and train classes, grouped as freight, intercity and regional (Table 3 , Table 4 and Table 5 show the emission factors used for the 2017 and earlier versions of the NAEI) are combined with appropriate activity statistics. Factors for locomotives that are no longer widely used (e.g. Class 37 and 47) are included since a timeseries of annual emissions from rail since 1970 is maintained in the NAEI. The most recent inventory year in the NAEI is 2018 (referred to as the 2018 NAEI); data for this and earlier years was published in May 2020. Refinements to the NAEI rail emission factors based on the current RSSB work and which were used in the 2018 NAEI are discussed in Section 10.2.2.

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[51] https://naei.beis.gov.uk/data/emission-factors

Table 3 Freight locomotive emission factors used for the 2017 NAEI

Units (g/km)	**Class 37**	**Class 47**	**Class 56**	**Class 58**	**Class 60**	**Class 66**	**New freight locos**
Fuel (kg/km)	3.6	5.3	6.8	6.8	6.4	4.8	4.8
CO	24.5	26.1	43.2	22.5	21.6	43.2	74.9
NOX	51.8	80.1	129.6	103.5	129.6	120.0[1]	81.3
HC	12.6	32	22.4	12	10.8	22.4	4.3
NMVOC	12.1	30.8	21.6	11.6	10.4	21.6	4.1
CH_4	0.9	1.2	0.8	0.4	0.4	0.8	0.2
Benzene	0.2	0.6	0.4	0.2	0.2	0.4	0.08
1,3-butadiene	0.1	0.3	0.2	0.1	0.1	0.2	0.04
PM_{10}	5.1	5.1	5.1	5.1	4.7	5.1	0.5

[1] This factor was revised from 387.5 g/km in earlier versions of the NAEI to 120 g/km for the 2017 NAEI.

Colour-coding key for data sources in Tables 3, 4 and 5:

LRC 1998 calculation methodology based on BR Research[52] and EWS testing data.
LRC calculation based on Technical University of Denmark work[53]. Calculations partially based on BR Research data[54] as one of the data sources.
Bombardier 2001 data and calculations used to replicate LRC calculation methodology.
AEAT 2001 calculation[55] replicating LRC methodology using Siemens data at rolling stock design stage.
AEAT 2001 calculation[56] using Alstom data to replicate LRC calculation methodology. Only one calculation was done to cover both Classes 175 & 180 despite them having different engines, transmissions and maximum speeds.
EMEP/EEA assessments[57, 58, 59] replacing original LRC data. One of the underlying data sources is the LRC work.
EWS supplied data.
AEAT 2001 calculations[60] based on maximum allowable emissions under a then future emission standard (was draft UIC3 at the time, later became rail Euro IIIA).

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[52] Wilkins (1994). *Determination of diesel exhaust emissions on British Rail*. British Rail Research, Materials Science Unit, Report LR-MSU-036.
[53] Jørgensen, M.W. and S.C. Sorenson (1997). *Estimating emissions from railway traffic*. Technical University of Denmark, Department of Energy Engineering, Report ET-EO-97-03.
[54] Wilkins (1994). *Determination of diesel exhaust emissions on British Rail*. British Rail Research, Materials Science Unit, Report LR-MSU-036.
[55] Hobson, M. and A. Smith (2001). *Rail and road emissions model*. Strategic Rail Authority.
[56] Ibid.
[57] https://www.eea.europa.eu/publications/EMEPCORINAIR4
[58] https://www.eea.europa.eu/publications/emep-eea-emission-inventory-guidebook-2009
[59] https://www.eea.europa.eu/publications/emep-eea-guidebook-2013
[60] Hobson, M. and A. Smith (2001). *Rail and road emissions model*. Strategic Rail Authority.

Table 4 Intercity passenger train emission factors used for the 2017 NAEI

Units (g/vehicle-km)	Class 180	Class 220	Class 221	Class 222	Class 43	Class 47+7	Class 47	Class 37
CO	5.4	1.9	1.9	1.6	4.8	20.0	13.1	12.3
NO_X	15.8	15.7	15.9	13.4	17.9	63.8	40.1	25.9
HC	0.2	0.5	0.5	0.4	2.1	5.8	16.0	6.3
NMVOC	0.2	0.5	0.5	0.4	2.0	5.5	15.4	6.1
CH_4	0.0	0.0	0.0	0.0	0.1	0.2	0.6	0.2
Benzene	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.1
1,3-butadiene	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
PM_{10}	0.3	0.4	0.4	0.3	2.4	4.1	2.6	2.6

Table 5 Regional passenger train emission factors (g/vehicle-km) used for the 2017 NAEI

Train class:	57	67	121	142	143	144	150	153	155	156
Train type:	Co'Co'	Bo'Bo'	Bubble car	Pacer			Sprinter			
CO	6.5	5.9	2.2	3.6	4.1	3.5	1.6	1.6	1.4	1.5
NO_X	14.6	13.3	55.7	18.8	21.1	18.2	40.5	40.6	36.5	37.0
HC	0.6	0.5	0.4	8.3	9.3	8.0	0.3	0.3	0.2	0.2
NMVOC	0.5	0.5	0.4	8.0	9.0	7.7	0.3	0.3	0.2	0.2
CH_4	0.0	0.0	0.0	0.3	0.3	0.3	0.0	0.0	0.0	0.0
Benzene	0.0	0.0	0.0	0.2	0.2	0.2	0.0	0.0	0.0	0.0
1,3-butadiene	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0
PM_{10}	0.7	0.6	0.3	0.8	0.9	0.8	0.2	0.2	0.2	0.2

Table 5 (continued) Regional passenger train emission factors (g/vehicle-km) used for the 2017 NAEI

Train class:	**158**	**159**	**165**	**166**	**168**	**170**	**171**	**175**	**185**	
Train type:	**Express Sprinter**		**Turbo**		**Turbostar**			**Coradia**	**Desiro**	**New trains**
CO	2.1	2.2	7.9	7.8	5.0	5.5	6.2	5.4	1.6	6.6
NO_X	17.3	18.3	20.3	20.0	14.7	16.2	18.2	15.8	13.5	3.7
HC	1.1	1.1	1.0	1.0	0.2	0.2	0.2	0.2	0.4	0.4
NMVOC	1.0	1.1	0.9	0.9	0.2	0.2	0.2	0.2	0.4	0.3
CH_4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Benzene	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1,3-butadiene	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PM_{10}	1.4	1.4	0.8	0.8	0.3	0.3	0.4	0.3	0.3	0.0

4.2 Derivation

A brief history of the source of the emission factors utilised in the NAEI is provided in this section. This enables their usefulness and applicability to be assessed.

For diesel locomotives and power cars, the NAEI emission factors are based on a combination of two main data sources from the early to mid-1990s: calculations and estimates done by the Technical University of Denmark with EU funding[61] and some limited British Rail Research completed in 1994[62] followed by testing and modelling in 1998 by the London Research Consortium (LRC; later to become part of Transport for London). These do not directly take account of real-world loadings, speeds or drive cycles but instead base the calculations on fuel usage (g/kg fuel used) as the most practical methodology available at the time, though it was already known at the time (and even more so with new work since) that the production of AQPs (with the exception of SO_2) is less directly related to energy consumption and the conditions in which the fuel is burnt is more important[63].

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[61] Jørgensen, M.W. and S.C. Sorenson (1997). *Estimating emissions from railway traffic*. Technical University of Denmark, Department of Energy Engineering, Report ET-EO-97-03.

[62] Wilkins (1994). *Determination of diesel exhaust emissions on British Rail*. British Rail Research, Materials Science Unit, Report LR-MSU-036.

[63] Heywood, J.B. (1988). *Internal combustion engine fundamentals*. 1st edn. McGraw-Hill Education.

Later work by the Technical University of Denmark from 1998[64, 65, 66, 67, 68] started to progressively introduce realistic drive cycles and the effect of combustion conditions on emissions. The 2005 work has addressed other pollutants apart from NO_X (which was still on a crude g/kg fuel used basis) but this work despite being well cited has not been widely utilised in others' calculations. The 2005 work still estimated NO_X (but not the other pollutants) on a simple generic g/kg fuel basis which helped perpetuate this methodology the last time emissions were assessed in detail by the UIC in 2004-2006, despite contrary testing and modelling from Germany[69]. The Danish work over the years was somewhat hampered by the prevalence of hydraulic transmission in both Danish locomotives and DMUs until very recently, combined with the lack of OTMR or telemetry on Danish rolling stock compared with other countries (again until relatively recently), made the work both less transferable to the UK and hard to carry out.

The newest emission factor in the NAEI freight locomotive emission factors was for the, then new, initial Class 66 locomotives and a new locomotive factor based on a draft of the UIC3 standard which would later become the rail Euro IIIA emission standard.

For diesel multiple units, the current NAEI emission factors are based on further sets of data: the older unit data has the same origin as explained above, along with some additional work to include then newly introduced stock when the Rail Emissions Model (REM) was being developed for the UK Department for Transport during 2001 by AEA Technology[70] (e.g. Class 168/170, 220/221/222 and refreshed High Speed Train, HST, data) along with some revised fuel consumption data from Atkins Rail.

More recently introduced stock such as the Class 172 DMUs were treated as 'new trains' in Table 5 . There was no emissions testing for this train class, so the assumption was compliance with Euro IIIA.

No work on diesel emission factors has been undertaken over the previous decade. This was partially driven by:

- expected large scale electrification, so the need for diesel rolling stock was anticipated to diminish at that time[71]

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[64] Jørgensen, M.W., and S.C. Sorenson (1998). ‘Estimating emissions from railway traffic’, *International Journal of Vehicle Design*, 20(1-4), 210-218.

[65] Bek, B.H, and S.C. Sorenson (1998). *Future emissions from railway traffic*. Technical University of Denmark, Department of Energy Engineering, Report ET-EO-98-02.

[66] Sorenson, S.C. (2000). ‘Energy statistics and railway emissions inventories’, *Proceedings of the UIC Energy Efficiency Conference*, Paris.

[67] Lindgreen E.B.G., and S.C. Sorenson (2003). ‘A model for the estimation of energy consumption and air pollutant emissions from rail transport’, *Proceedings of Environment and Transport*, INRETS: 175-181.

[68] Lindgreen, E.B.G., and S.C. Sorenson (2005). *Simulation of energy consumption and emissions from rail traffic*. Technical University of Denmark. Department of Mechanical Engineering, Report MEK-ET-2005-04.

[69] Hill, N., S. Kollamthodi, S. Cross, T. Hazeldine, M. Bergendorff, M .Halder, T. Köhler, R. Collin, J. Bittner, P. Scherm, S. Müller, R. von Bischopinck, H. Gehrig, R. Schwarzenau and W. Kinzel (2005). *Rail Diesel Study, WP2 Final Report: Technical and operational measures to improve the emissions performance of diesel rail*. UIC.

[70] Hobson, M. and A. Smith (2001). *Rail and road emissions model*. Strategic Rail Authority.

[71] For instance, a large order of Class 170 and 185 DMUs had been considered in 2007-2009 but the need was removed by the start of electrification projects in the Manchester and Leeds areas.

- the rail sector accounting for a small proportion of total NO_X and PM emissions in the UK as a whole, so improvements of emission estimates for this sector have been seen as a low priority.

Consequently, there are large knowledge gaps for rail emission factors that now need to be filled, especially now that air quality concerns have risen up the public agenda.

4.3 Limitations

The previous NAEI rail emission factors (in units of g/km) are of limited use in more detailed studies (such as local, regional and multi modal studies) because of various reasons and these are discussed below.

4.3.1 Calculation methodology cannot account for heterogeneity in drive cycles and operating parameters

For activity statistics the NAEI rail emissions methodology uses train mileage data by locomotive and train class from the Department for Transport's (DfT's) Rail Emission Model (REM) which was originally developed for the Strategic Rail Authority (SRA) in 2001[72]. REM can be refreshed with new data, but this involves substantial effort. The latest REM data used in the NAEI is for 2011, 2014 and 2018 with interpolations of intervening traffic changes based on changes in Office of Rail and Road train mileage and freight lifted data.

NAEI emission estimates are then derived by multiplying these activity statistics by the relevant locomotive and train emission factors (in units of g/train-km or g/vehicle-km) which are covered in Section 4.1. However, these emission factors have been calculated in many different ways and often with proxy values which do not necessarily directly relate to the engines concerned due to lack of data.

Currently for the NAEI, normally only one diesel rail emission factor is used per pollutant per kilometre travelled for each generic train class. These g/km emission factors for freight locomotives are based on a single drive cycle that assumes averages for certain amounts of time spent at:

- full engine output
- idle
- some selection of intermediate engine outputs.

No account is taken of variations in:

- sub-classes (e.g. different equipment or gearing)
- speeds
- loadings

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[72] Hobson, M. and A. Smith (2001). *Rail and road emissions model*. Strategic Rail Authority.

- distances between stops
- gradients.

These g/vehicle-km emission factors for passenger rolling stock (which were on a g/train-km basis until being rebased in 2011) were calculated from an underlying g/kg fuel used basis, mostly using theoretical drive cycles created by Atkins Rail in 2001 (or by Siemens for the Class 185). These emission factors partly reflect typical route profiles that the rolling stock were utilised for at the time, i.e. density of station stops and max running speeds but not gradient issues (uniquely addressed by the Class 185). This approach allowed fuel usage to be estimated as in many cases the emission factors were originally calculated on a g/kg fuel-used basis.

As discussed in Section 2, the production of most air pollutants is not linearly related to engine power output or fuel consumption. The NAEI emission factors are simple averages and take no account of varying engine behaviour and hence real-world emissions under particular operating conditions. There are many different ways to expend varying amounts of energy and thus generate varying amounts of AQP and GHG emissions when travelling the same distance, and these ways are not captured by a simple g/km emission factor. Furthermore, often the interest in air quality issues is not in the average emissions behaviour of a train but in the evaluation of local impacts under specific operating conditions. For instance, this may be in extensive periods of idling in enclosed stations where train emissions will be above those based on averages.

As a summary, the current NAEI methodology uses emission factors on g/km basis which are averaged and as such are less relevant for analysis of local air quality problems. Stationary (with engines idling), slow moving or accelerating trains can have higher than average emissions that are dispersed over a comparatively small area so total concentrations locally can be quite large (see Section 2.9).

4.3.2 Source data quality, data completeness and assumed drive cycles

There is a large degree of uncertainty regarding the data underlying the current emission factors which are often up to 25 years old. Information about the drive cycles is poorly known and those that are known are too simplistic. The quality of the original testing cannot currently be established since the relevant BR Research Report from 1994[73] has apparently not been archived and therefore cannot be accessed.

At least some of the current NAEI emission factors will be too high for certain locomotive or train classes or subclasses. For instance, later Class 66s are Euro IIIA compliant and so a single emission factor for all locomotives in this class is unlikely to be representative.

Most of the current UK rail emission factors are based on testing done for the European test cycle which provides a standardised way of testing (ISO 8178:F). However, these

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[73] Wilkins (1994). *Determination of diesel exhaust emissions on British Rail*. British Rail Research, Materials Science Unit, Report LR-MSU-036.

test measurement requirements have remained unchanged since 1982 until being replaced with ISO 8178:C1 in 2015. This particular drive cycle, originally developed by Deutsche Bundesbahn for large MTU engines in diesel hydraulic locomotives, covers 25% in full throttle, 15% in half throttle and 60% in idle and is used to aggregate the individual test mode into a single number as explained in Section 3. (As will be discussed later in this report, this average drive cycle is not fully representative of engine operation in most GB locomotives or rolling stock, where overall time in idle is typically higher and less time is spent in full throttle.)

The single aggregated factor was converted to a per fuel usage basis and then to a g/km basis that is then used in the NAEI calculations or even in some case generic emission factors on a fuel usage basis (then converted to a g/km basis) from the Technical University of Demark work[74] that do not relate to the specific engines in the rolling stock but an average across many different engine types.

4.3.3 Use of conservative values

The previous NAEI emission factors for 'new' freight locomotives (for example as used for Class 68, Class 70, and the most recent batch of new Class 66) and for 'new' regional passenger trains (Class 172) assumed the Euro IIIA emission standards emission factors would be met exactly. This approach relates the fuel energy consumed to the g/kWh values in the standards. Average fuel use per distance travelled in the standard drive cycle can then be used to derive a g/km emission factor.

However, these emission factors are conservative values that assume the emissions are the maximum values permitted by the emission standards. In practice, these locomotives and trains would have lower emissions since compliance requires meeting 90% of the emission standard in order to allow for variance in individual engines, i.e. to ensure the majority of engines manufactured will have emissions below the threshold. Furthermore, in some circumstances, specific test data for certain engines shows that emissions of some pollutants are significantly below the relevant emission standard threshold. There are, therefore, advantages in using real testing data to develop emission factors as the actual emissions are likely to be lower.

4.3.4 Use of proxy values

Since no emissions testing data was available at the time for the Class 175, the same emission factors for the Class 180 are currently used in the NAEI, despite these classes having different speed limits, engines and gear boxes, all of which can be expected to lead to a different emissions profile. Similarly, no test data was available for the Class 185 so the same emission factors for the Voyager (Class 220) were used. While the Class

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[74] Lindgreen E.B.G., and S.C. Sorenson (2003). ‘A model for the estimation of energy consumption and air pollutant emissions from rail transport’, *Proceedings of Environment and Transport*, INRETS: 175-181.

185 has the same engine as the Voyager, it has hydraulic rather than electric transmission and so, likewise, a different emissions profile can be expected.

4.3.5 Recent fuel quality improvements not accounted for

The off-road diesel and fuel oil standard BS 2869 A2 was amended in 2010 to align with required changes under the Fuel Quality Directive (2009/30/EC). Key changes were a reduction in the fuel sulphur content to 10 ppm and limiting the PAH content to 8%. These improvements to fuel quality will also have helped reduce rail emissions, but there has been only limited emissions testing subsequent to this transition which started over a decade ago and had to be completed prior to 2012, and therefore there has been limited incorporation of its impacts into the previous NAEI emission factors.

Reducing the sulphur contained in diesel leads to a decrease in formation of SO_2. While SO_2 emissions are not in scope for this project, this change can be expected to have reduced PM emissions. This is because a proportion of the PM (typically 20-25% of PM) derive from the formation of particulates nucleated on sulphur-containing molecules.

Therefore, the introduction of ultra-low sulphur diesel (ULSD) has virtually eliminated the production of SO_2 and sulphur containing PM. This change is not reflected in the current PM emission factors: a 20-25% reduction in the mass of PM produced would be expected if the change was taken into consideration.

The processes used in refineries to reduce fuel sulphur levels also have the beneficial side-effect of moderately reducing the polycyclic aromatic hydrocarbons (PAH) content of the fuel, which in turn leads to reduced particulate and NO_X formation (further PAH reduction would also see further reductions in PM and NO_X) - see studies[75] on the use of Mk1 specification diesel in Sweden over the last two decades).

As well as requiring reduction in sulphur content, the introduction of the current rail fuel specification (matching road specification fuel) has also involved the addition of cetane enhancers to the fuel which promote an earlier and slower start to combustion reducing the production of both particulates and NO_X. However, no testing has been carried out on GB rail engines to quantify the full impact of non-sulphur changes under the latest fuel standard.

4.3.6 Use of data that is no longer applicable

Various locomotives (e.g. Classes 43, 57 and 73) have been re-engined with cleaner engines that met more recent emission standards since the previous NAEI emission factors were developed. Thus, the previous NAEI factors can be expected to be too high. For instance, the Paxman Valenta engines (which were not subject to any emission standards) in all HSTs (Class 43) were replaced with cleaner engines (all essentially Euro IIIA compliant) around 10 years ago. This is particularly important since these trains

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[75] Danielsson, D. and L. Erlandsson (2010). *Comparing Exhaust Emissions from Heavy Duty Diesel Engines using EN590 vs. MK1 Diesel*. Swedish Transportation Administration.

have accounted for a large proportion of distance travelled and diesel used in recent years (about 20% of all rail diesel usage till recently). In addition, short formation HSTs are now being deployed and are expected to be in use for another 10 years. Since these units will be lighter and will have different operating profiles, their fuel consumption and emissions will be different from the long formation HSTs.

4.3.7 Instances where factors are too high

The Class 66 has been the mainstay of GB rail freight haulage since the late 1990s. The original NO_x emission factor of 387.5 g/km (for the original locomotives that would have met the US Tier 0 emissions standard) had been recognised as too high and was revised down by the SRA in 2001 to 120 g/km[76]. However, with the SRA's demise, both sets of methodologies and calculations were lost and the factor used in the NAEI reverted to the original figure. Concerns about this high emission factor (3 to 4.5 times higher than for comparable locomotives) were raised by freight operators in 2018.

In response to these concerns, detailed calculations and Monte Carlo simulations were carried out to show how non-NO_x US EPA emission testing data would have been converted into the other NAEI Class 66 emission factors for other pollutants. Sense checks against the maximum NO_x emissions permitted by regulations at the time were made possible due to a detailed understanding of fuel consumption in each power setting (enabled by review of FOC-provided OTMR) and potential drive cycles that would have been used to develop a g/km factor.

After assessing standard drive cycles alongside fuel consumption and non-NO_x emissions testing data, a good match with the US linehaul non-dynamic brake drive cycle was identified. This would have been the most likely candidate at the time of the original work. The calculation for NO_x was then replicated, demonstrating that the probable matching NO_x factor was slightly lower than the SRA original. While it cannot be proved, it is likely that the ultimate cause was a simple 3.6 times unit conversion error. Thus, use of the SRA's revised value of 120 g/km was justified as a better emission factor. Incorporation of this factor in the 2017 NAEI (published in Spring 2019) resulted in reductions of around 10,000 tonnes of NO_x in each annual inventory back to 1998[77].

As another example, the 2014 Kings College London study[78] measuring emissions adjacent to the GWML near Ealing and the ECML near Finsbury Park struggled to detect rail emissions above road-dominated background levels which came as a surprise to the study authors whose expectations had been based on the previous NAEI emission

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[76] Hobson, M. and A. Smith (2001). *Rail and road emissions model*. Strategic Rail Authority.

[77] Richmond, B, A. Misra, M. Broomfield, P. Brown, E. Karagianni, T. Murrells, Y. Pang, N. Passant, B. Pearson, R. Stewart, G. Thistlethwaite, D. Wakeling, C. Walker, J. Wiltshire, M. Hobson, M. Gibbs, T. Misselbrook, U. Dragosits and S. Tomlinson (2019). UK Informative Inventory Report (1990 to 2017). Ricardo Energy & Environment.

[78] Fuller, G., T. Baker, A. Tremper, D. Green, A. Font, M. Priestman, D. Carslaw, D. Dajnak, and S. Beevers (2014). *Air pollution emissions from diesel trains in London*. Environmental Research Group, King's College London.

factors. This finding indicated that these emission factors were likely to be too high for the HST, DMU and freight locomotives running on these lines at that time.

4.3.8 New rolling stock not covered

The previous NAEI emission factors were developed during a phase of work predominantly carried out 18-27 years ago and have not been subsequently updated in detail. These factors cover a large proportion of the current GB passenger fleet. The engines, drive trains and emission controls for most current passenger units have not changed since their introduction. However, while the composition of the GB diesel passenger rolling stock fleet largely remained static over the last decade, large changes have recently or are currently taking place due to completion of electrification projects (and associated stock cascades), franchise changes and responses to ensure compliance with the Persons of Reduced Mobility (PRM) requirements by 2020.

Since the NAEI emission factors were developed:

- new locomotives have been introduced (Classes 68 and 70)
- locomotives have been re-engined (e.g. Classes 43, 57 and 73)
- new passenger trains have been introduced (e.g. Classes 172, 195, 755, 800 and 802)
- completely new engine types have been introduced (e.g. MTU1600 series used in the Class 800/802 Intercity Express Trains (IET), Caterpillar C175 engine used in the Class 68 and GE PowerHaul P616 engine used in the Class 70)
- existing engine designs have been updated to comply with revised emission regulations so more recently supplied versions of engines will have lower emissions (e.g. EMD 710 engine in Class 66, MTU 183/1800 engine used in many regional DMUs manufactured over the last 20 years), however there are no specific factors to take account of this
- after-treatment technologies (such as diesel particulate filters to reduce PM and Selective Catalytic Reduction to reduce NO_X) have been deployed, all focusing on addressing the challenges of meeting newer emissions standards.

New rolling stock delivered over the last decade is assumed as having complied with the maximum allowed by the Euro IIIA standard, even though real-world emissions may be lower. Indeed, the most recent batch of Class 68 deliveries along with more recent and soon to be deployed rolling stock (e.g. Classes 195, 196, 755, 769, 800 and 802) will meet the Euro IIIB standard for which there are no NAEI emission factors in g/vehicle-km available.

4.3.9 Limited applicability to intermodal comparisons

While emission factors in g/km are available for the freight rail sector they are not suitable for comparisons of environmental performance between transport modes as no account of tonnage hauled is taken into account. Furthermore, as the typical volumes of freight per train have increased over time so emissions per train will have increased, but emissions per tonne carried will have decreased. Emissions per tonne-km are variable depending on cargo type: for example, the tare weight of wagons as a fraction of overall train weight varies by up to 15% of total train weight for different cargo types.

4.3.10 Summary of issues

While the NAEI emission factors in units of g/km can be used for high-level comparisons between locomotives and rolling stock classes, as well as for broad modal comparisons, the current factors are uncertain and insufficiently detailed to act as a baseline against which the effects and costs of specific emission reduction options and modifications can be evaluated. They also do not permit the granular evaluation of low speed situations (e.g. major stations, freight yards) where concerns about air quality are likely to be the greatest.

The current emission factors therefore need to be improved to benefit national, regional and local decision making. There is a clear need to improve and expand the available emission factors to cover the current and expected future GB rolling stock fleet.

5 Why emission factors on a delivered energy and notch basis?

Sources of emissions and emission standards (which are in units of g/kWh) have been reviewed in previous sections. Available GB rail emission factors (as used in the NAEI) are in units of g/km but there are a number of limitations. The benefits of developing emission factors by notch, in units of g/kWh, are discussed in this section.

5.1 Emission factor units of g/kWh

Emission factor units on a per kilometre or per tonne of fuel consumed basis, are of limited use in more detailed studies, such as modal comparisons or local air quality studies. As emissions of most air pollutants are not directly proportional to fuel consumption they will substantially vary depending on the particular (real world) drive cycle. Factors in g/kWh relate emissions to the usable energy produced by the engine under certain conditions. Internationally, across multiple sectors, internal combustion engine emission testing and emissions standards are set in units of g/kWh and based on a given drive cycle. For rail diesel engines, the power generated is usually measured in kW. Most rail diesel applications have fixed pre-set throttle levels that correspond to fixed power outputs, thus power/notch factors (measured in g/kWh, i.e. emissions per unit power) are based on the physical operation of the engine and notches are well-known and used extensively in the rail sector outside of the UK. In addition, this unit of measure is well understood in terms of diesel or petrol engines across different transport sectors.

Examples of countries using g/kWh factors for rail include:

- the US, which started systematically measuring rail emissions in this way in 1972 and g/kWh became the federally mandated measurement underpinning emissions regulations in the early 1980s (albeit with the use of grams per brake horsepower hour as the statutory unit of measurement despite measurement of the power during testing being mandated to be in metric units)
- Australia, where a g/kWh basis has also been adopted.[79]

European engine emission testing across all sectors measures emissions in g/kWh (see Section 3) to derive a single aggregated factor based on certain test points (for which specific results are not published) and not at realistic individual engine operating modes/notches.

Consequently, emission standards typically use this metric and a large range of testing data are already available, particularly from the US for locomotives where regulatory testing data is published by the US EPA. The example in Figure 21 is from 1994 for a mechanically governed engine that was already 19 years old and one of the earliest engines produced after the start of US notch-based testing regime. Current raw testing

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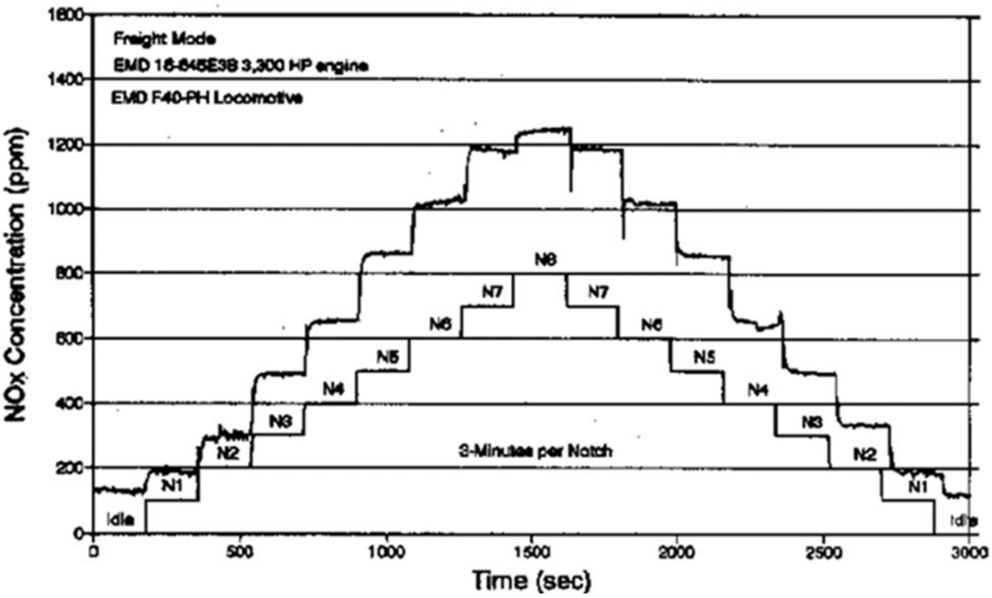
[79] ABMARC (2016). *Diesel locomotive emissions upgrade kit demonstration project – Fuel efficiency, emissions and noise testing*. NSW EPA.

data (with longer times in each step as computer memory capacity is no longer an issue) shows similar stable emissions in each notch.

Figure 21 US EPA testing data for the EMD 16-645-E3B engine manufactured in 1975, tested in 1994. Chart shows NO_x emissions (upper line) as well as the notch steps at 3-minute intervals during the test.



Emission factors in units of g/kWh offer an improved method to characterise and evaluate measures to reduce diesel engine emissions. They can be used to understand energy usage and emissions generated in all parts of a drive cycle, which in turn can vary significantly for the type of service and loadings. Essentially, emission factors in g/kWh can incorporate sufficient granularity to reflect real world conditions and variability and therefore allow accurate modelling of rail emissions.

Engine fuel efficiency under different operating conditions has traditionally been measured as fuel use per unit power in g/kWh[80]. This therefore allows direct comparison of fuel consumption with all emissions in the same measurement conditions and in the same units, unlike other metrics such as g/km. Traditionally 200 g of fuel per kWh has been seen as the most efficient a diesel engine for rail use can achieve, but some engines can now attain better than 200 g/kWh under limited conditions. For all engines for rail use manufactured in the last few decades, the amount of carbon in fuel leaving the engine as CO_2 is ≥98% at idle and ≥99.8% under higher power conditions, which allows the specific fuel consumption to be used to accurately calculate CO_2 emissions under a whole range of engine running conditions.

For the calculation of CO_2 emission factors, static test bed measurements were used if available and if not then calculations based on fuel consumption were made as a minimum of 99.85% of the fuel used in the rail engines considered in this study is

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[80] Also known as brake specific fuel consumption, BSFC, in automotive terminology.

converted to CO_2, hence a conservative assumption of 100% conversion of carbon in fuel being converted to CO_2 was used, assuming a typical value of 2,598g CO_2/litre of diesel fuel that has been measured in recent UK engine testing.

5.2 Engine notches

In order to allow rolling stock from different manufacturers and performance specifications to operate together in the era before computerisation of engines or rolling stock without different locomotives (diesel or electric) or multiple units (electric or diesel) 'fighting' each other, various standards were developed in different countries to allow simple electronic selection of a limited number of notches or fixed power output levels (defined as a % of max engine power or electrical alternator output in the diesel electric transmission case and as a proportion of maximum fuel supply rate and hence increasing proportions of the engine’s rated maximum power curve in the diesel hydraulic and mechanical transmission cases).

In Great Britain there are four main notch systems relevant to current diesel stock usage:

- The Sprinter notch system has 8 notches from Idle to 7 (notches typically set at 0%, 8%, 17%, 41%, 56%, 68%, 82% and 100% with some small variations depending on the transmission differences) covering DMU Classes 142-172 (in practice some wiring differences limit interaction in some cases).
- The US Association of American Railways (AAR) notch system developed in the 1960s covering many more modern GB locomotives (Class 57, 59, 66, 67, 68, 69 and 70). It has 9 notches from Idle to 8 (typically set at 0%, 6%, 12%, 22%, 33%, 43%, 52%, 78%, 100%).
- The HST notch system has 6 notches from Idle to 5 (set at 0%, 5%, 13%, 30%, 45%, 79%, 100%).
- The Voyager/Meridian and the IET rolling stock families have extensive computer control of rolling stock and engines and significantly more notches.

5.3 Developing emission factors by notch

Emission factors by notch can be created by combining:

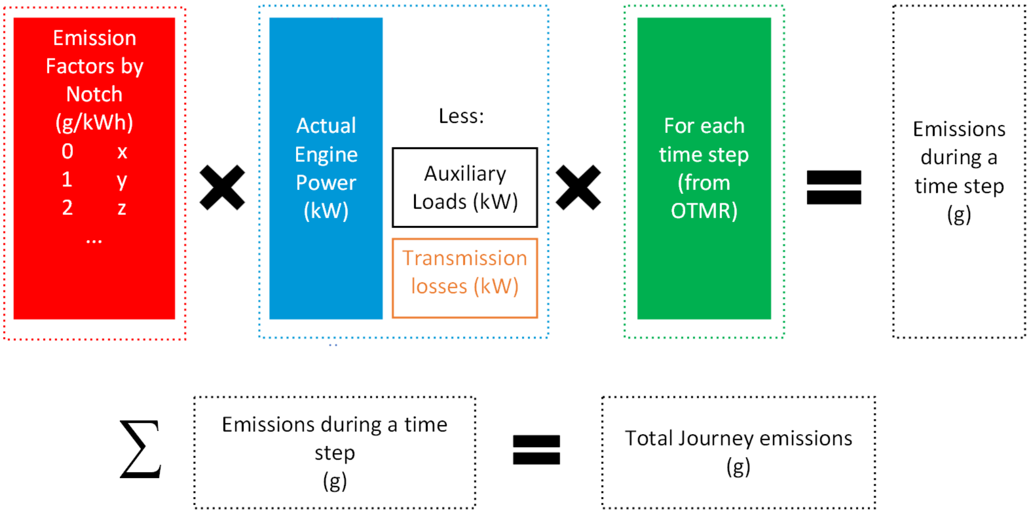
- high accuracy static testbed emissions testing (needed for engine certification)
- engine and rolling stock technical data (including auxiliary load data)
- OTMR data

Notch-based emission factors for fuel, CO_2, NO_x and PM were developed as part of the project. These emission factors also include auxiliary loads, for example in all cases the power used to drive air compressors that supply the braking system. For passenger rolling stock, the auxiliary loads include electric power for heating ventilation and air conditioning (if fitted), often referred to as the 'hotel load'.

In the case of electric transmission rolling stock, the notch-based emission factors also include losses in the transmission system as these are far less speed dependant (typically an order of magnitude less variation) than for hydraulic or mechanical transmission. DMUs with mechanical and diesel hydraulic transmissions are potentially more complex to develop emission factors for than trains with electrical transmission. Since the transmission efficiency varies a lot more with speed, more detailed OTMR data is needed to understand speed, transmission efficiency and thus the notch to emissions relationship. Combining the emission factors with OTMR allows more realistic emission estimates at all scales to be determined. See Sections 7 and 8 for a more detailed discussion of this issue.

To analyse OTMR data, a vehicle is assumed to remain in the same state until the next entry. The time difference between an entry (row i) and the next entry (row i+1) is the timestep, for which the train travelled at the speed and throttle setting as recorded in row i. The energy used in each timestep (kWh) can then be calculated by multiplying the typical nominal power usage at the engine (kW) for the train type and throttle setting by the duration of the timestep (h). The energy used in this timestep is then multiplied by emission factors (g/kWh) to determine the emissions (g) of the relevant pollutant (CO_2, NO_x or PM) produced in that timestep. A summary of this methodology is shown in Figure 22 .

Figure 22 Schematic summary of methodology for calculating emissions using emission factors by notch and OMTR data



5.4 Benefits of emission factors by notch

The multiple benefits of emission factors by notch are listed below.

5.4.1 Cost effectiveness through wide application

Emission factors by notch can be applied to different real-world circumstances through the use of OTMR data to model real drive cycles in different circumstances. As such they enable a limited amount of high accuracy stationary emissions test data to be applied to numerous circumstances (e.g. different drive cycles for the same train or the same engine is utilised with a different transmission). This approach therefore has potential benefits over portable emissions measurement system (PEMS) testing which can be very route specific unless conducted very carefully with other data collection in parallel, and which can require modification of exhaust systems and is therefore potentially quite expensive.

5.4.2 Better granular understanding of emissions generation

It is important to note, that while it is possible to derive other metrics such as g/km, g/tonne-km and g/passenger-km from emission factors in g/kWh, it is not possible to understand variations in energy used versus distance travelled, acceleration/deceleration and loadings from these other metrics. There is complete reliance on the underlying average drive cycle and loadings that will have been used to derive these emission factors (see Section 4). While emission factors in g/km and g/tonne-km can be used for high-level comparisons between transport modes, they are not suitable for understanding local air quality impacts[81] or for a detailed analysis of the benefits and costs of specific emissions mitigation measures.

Instead of g/km and g/tonne-km based factors, factors for fuel consumption per notch allows better evaluation of fuel use reductions. For example, the introduction of technology measures or changes in driver behaviour can be more directly linked to fuel savings. By using OTMR from different services (e.g. fast versus stopping), geography and loadings it is possible to better understand how energy use and emissions can vary even while travelling the same fixed distance. In addition, and of particular importance, is that emission factors in g/kWh can be used to directly understand emissions generated in idle, such as in enclosed railway stations or urban freight yards.

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[81] For example, within stations and freight yards or accelerating within 500 m of such locations.

5.4.3 Ability to develop and refine g/km factors

Emission factors in notch and g/kWh can serve as a key foundation on which to build emission factors in other units. For instance, it is possible to derive emission factors in terms of g/km by combining g/kWh emission factors with OTMR data on the distance travelled while the engine is in a certain notch (power output).

5.4.4 Ability to develop accurate g/tonne-km factors

Emission factors in g/kWh can also be combined with OTMR data on engine output and with trip timings and train loadings from TRUST (the Network Rail system used for monitoring the progress of specific trains and tracking delays on the rail network) to integrate a complete picture of emissions across a specific train trip and thus derive a much more accurate emission factor in g/tonne-km which can be used in comparisons with other modes of transport.

5.4.5 Improved modelling of emissions

Compilation of emission factors by engine notch and in units of g/kWh could be used to improve the DfT’s REM, and by combining with OTMR data will provide a more accurate baseline to then better understand the impacts of a range of factors, from small to large scales, e.g. emission controls, network pathing, infrastructure changes and infill electrification projects. Another application is detailed spatial mapping of rail emissions, currently being addressed in RSSB Project T1186 *CLEAR: Rail Emissions and Air Quality Mapping*.

5.5 Summary

Emission factors by notch can be used at a range of scales, to provide more accurate national or high-level emission totals as well as evaluating local impacts, particularly of idling trains which have been identified as being of key importance.

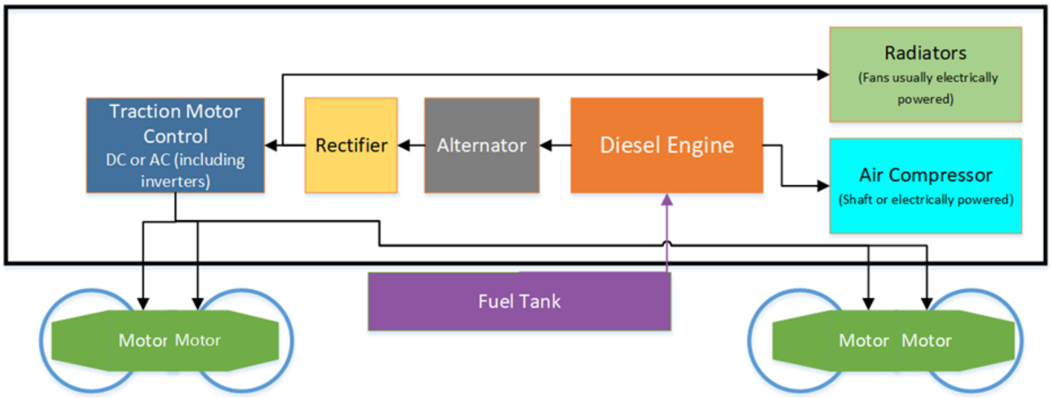
6 Methodological approach: Diesel electric transmission

This section and the following two sections describe how emission factors by notch can be derived for each type of transmission. Diesel electric transmission is discussed first in this section since it is the simplest as well as the most prevalent of the transmission types. This is followed by discussion in Section 7 of diesel hydraulic transmission which is also quite widespread in the UK. Finally, diesel mechanical transmission is discussed in Section 8 which is the least prevalent transmission type.

6.1 General principles

A diesel engine drives an alternator from which alternating current (AC) is converted by a rectifier to direct current (DC) to then feed motor control electronics that drive either DC (on older stock) or AC (on newer stock) traction motors. Some parts of the mechanical power generated may be used to drive air compressors to provide brake pressure. Part of the electrical power will be used for auxiliary loads which will include radiator fans, cabin heating and carriage heating and lighting (if applicable), as well as for, in some cases, driving air compressors (see Figure 23).

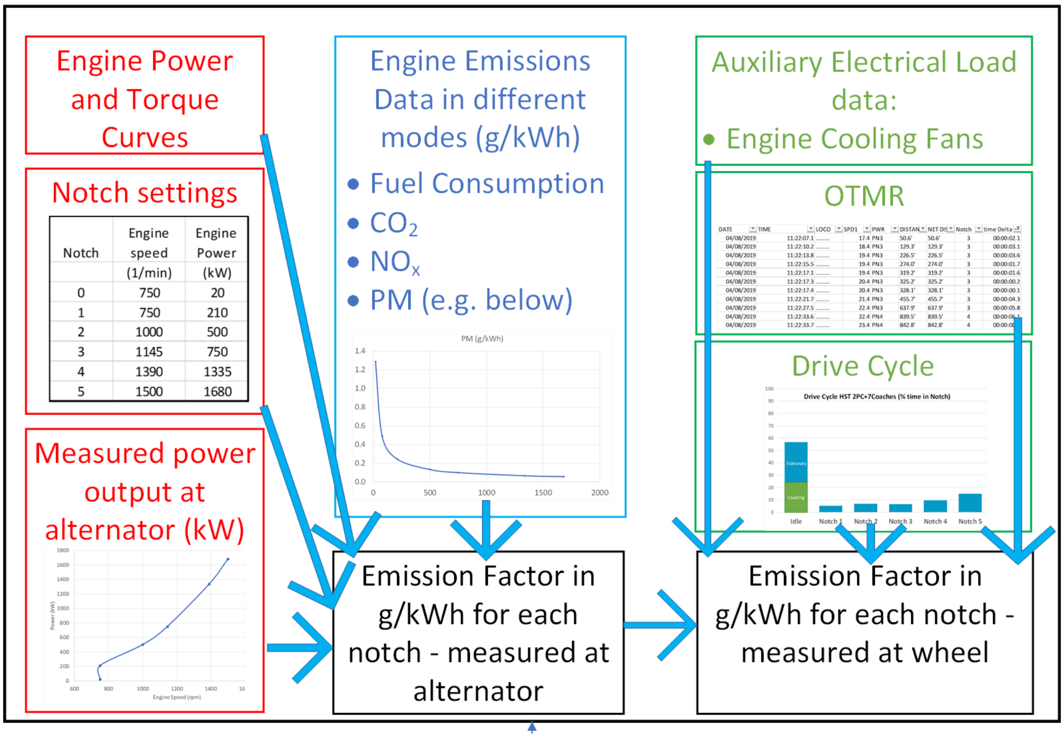
Figure 23 Schematic of diesel electric transmission



Data required to develop emission factors by notch are:

- engine data (power curves, notch setting, fuel consumption curves)
- engine emissions testing at various power outputs
- drive cycle/OTMR data.

Figure 24 Flowchart illustrating methodology for determining emission factors by notch for diesel electric transmission



Notch	Engine speed (1/min)	Engine Power (kW)
0	750	20
1	750	210
2	1000	500
3	1145	750
4	1390	1335
5	1500	1680

This example is for the HST and was based on operator, ROSCO and manufacturer data. The existing NAEI emission factors for the HST still assume Paxman Valenta engine data from the 1994 BR Research[82] study used by LRC to create emission factors on a per train-km basis and later rebased on a per passenger vehicle-km basis. The HST fleet was re-engined a decade ago with mostly the MTU 16V4000 engine (for increased reliability and reduced fuel consumption). This engine would have needed to be compliant with the UIC2 emission standard, however, for all pollutants apart from NO_X it is compliant with the Euro IIIA levels (and for NO_X is just above the Euro IIIA threshold). Given that the original Paxman Valenta engine was not compliant with any emission standards at all this will represent a significant mitigation of emissions.

Limited ISO 8178-F cycle emission test data for the HST engine variant (idle increased by 150 rpm and maximum throttle decreased by 300 rpm vs the 'standard' MTU 4000 series engine in order to match the HST alternator) was supplemented with other 4000 series engine data from MTU.

The drive cycles were based on engine control unit (ECU) data, terminus engine shut down policies (the power car at the concourse end is shutdown while in a terminus station) and total daily diagramming[83]. HSTs are currently used in three different configurations with varying numbers of passenger coaches between the two power cars:

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[82] Wilkins (1994). *Determination of diesel exhaust emissions on British Rail*. British Rail Research, Materials Science Unit, Report LR-MSU-036.

[83] Diagrams refer to the individual daily schedules for units or trains.

the combinations being 2 power cars and either 4, 7 or 8 passenger coaches. Later in 2020 a fourth variation with 5 passenger coaches will start to operate. The drive cycles developed from either ECU or OTMR data can therefore be used to take account of the various different operating combinations and the drive cycles for the 4, 7 and 8 coach combinations are shown below in Figure 25 , Figure 26 and Figure 27 . The drive cycle shows the expected behaviour of reduced time in idle and lower notches and increased time in higher notches as the number of carriages increases. In Figure 26 the split between stationary and coasting while the engine is in idle is shown. In previous rail emission factor work limited attention has been paid to the role of coasting yet it is important to note useful work (distance travelled) occurs in this condition.

OTMR is needed both to take account of transmission losses as power usage is measured at the alternator (not at the wheel) with diesel electric transmissions and to produce drive cycles/aggregated emission factors or to enable conversion of emission factors in g/kWh to other units such as g/vehicle-km.

Figure 25 HST drive cycle for 2 power cars + 4 passenger coaches with maximum 100 mph running

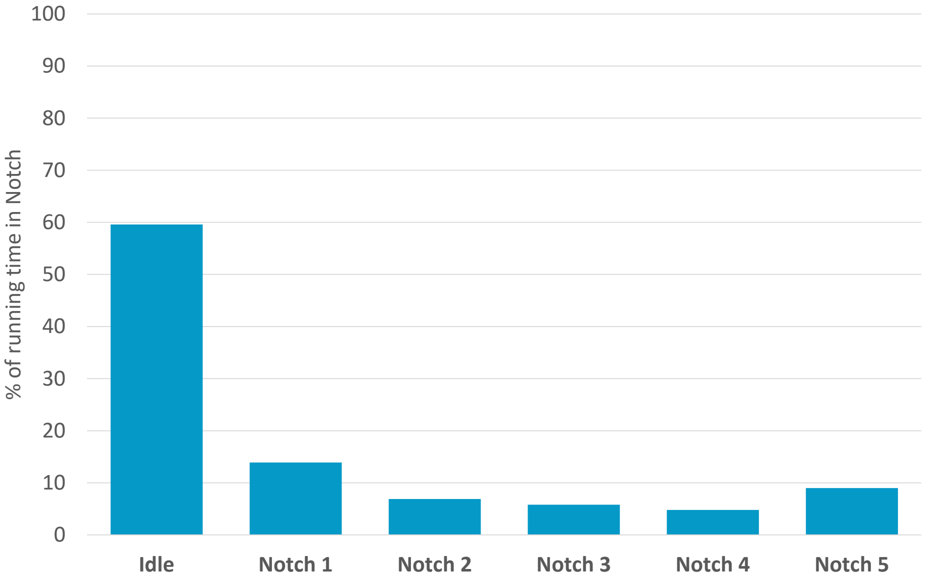


Figure 26 HST drive cycle for 2 power cars + 7 passenger coaches with maximum 125 mph running

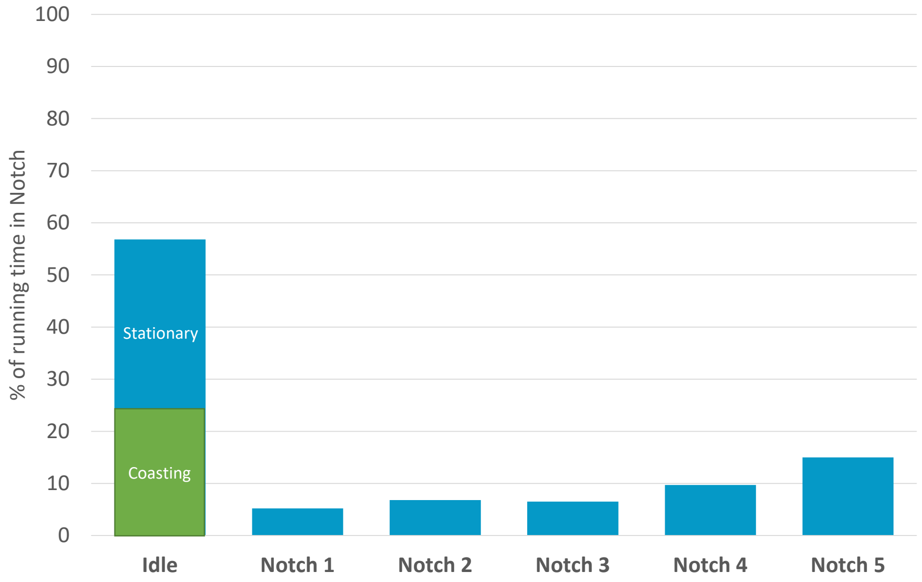
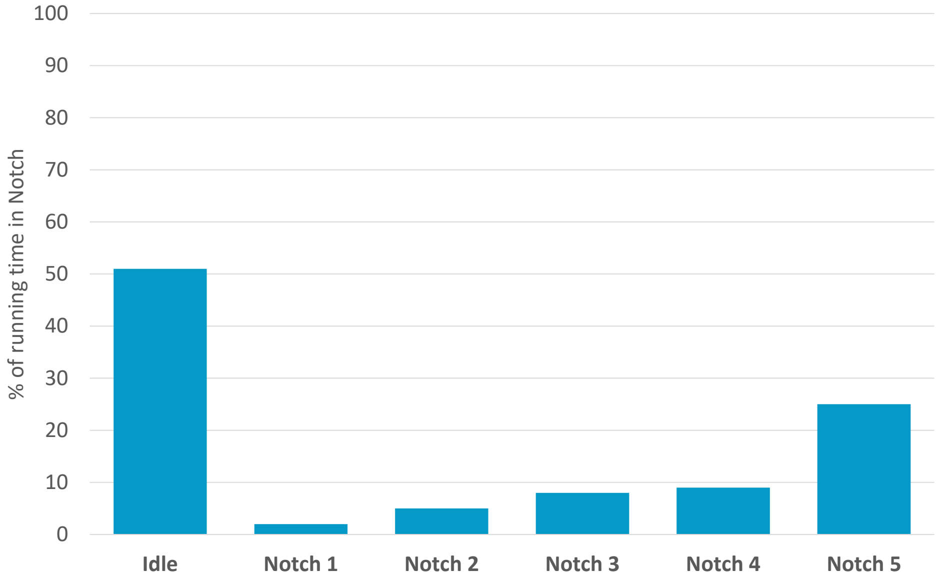


Figure 27 HST drive cycle for 2 power cars + 8 passenger coaches with maximum 125 mph running on frequent stopping diagrams



The first and third drive cycles above represent the least (2 power cars + 4 coaches) and most (2 power cars + 8 coaches) aggressive drive cycles respectively. The engines are in idle 60% (for 2+4) and 51% (for 2+8) of the time, respectively. Idle is therefore important for AQP production no matter what the drive cycle as it is the majority operating mode, although there is a large difference between the time spent in Notch 5 respectively 9% (for 2+4) versus 25% (for 2+8).

Figure 28 NO$_X$ emissions by notch for the HST MTU 16V4000R41R engine

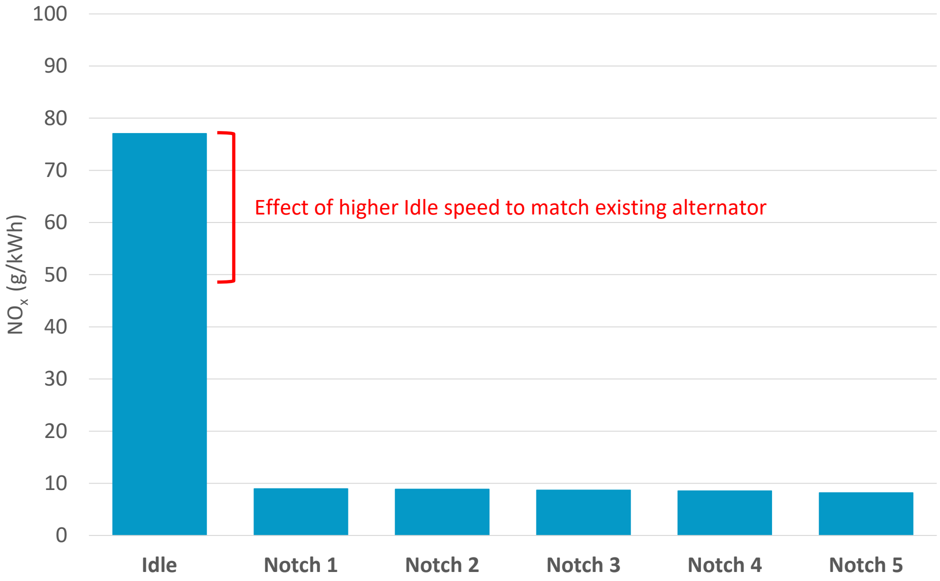
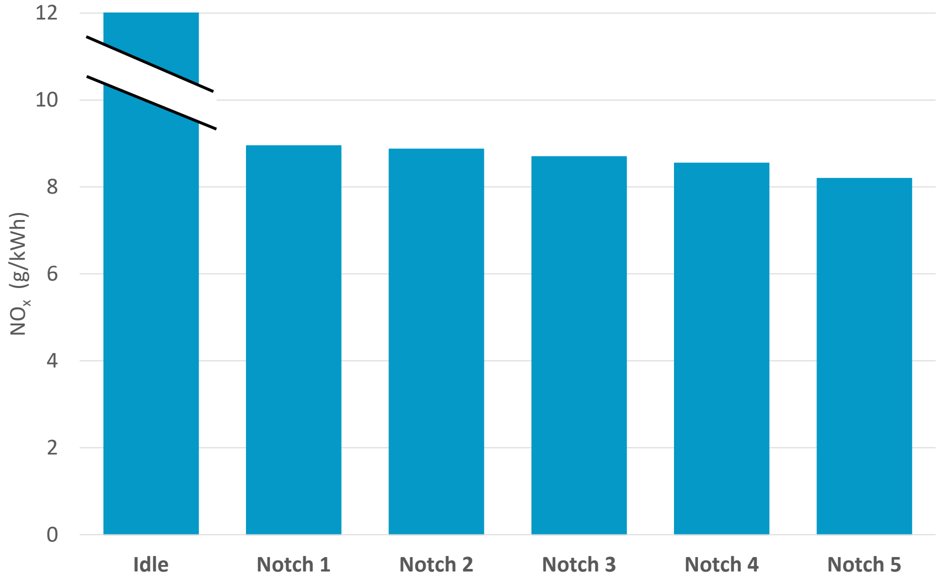


Figure 29 below shows NO$_X$ emissions by notch for the HST MTU 16V4000R41R engine, but with a reduced y-axis to show that there is variation between Notches 1-5 which is not clearly visible in Figure 28 . The variation in AQP production in Notches 1-5 and in power output is less with this engine than any others studied as the engine has an increased idle speed and reduced maximum speed (by 300 rpm) to enable a simple retrofit and reuse of the existing alternator, traction electrics and motors. The variation in NO$_X$ emissions with power output is therefore lower than for other engines as Notches 1-5 cover a narrower mid-range of the engine.

Figure 29 NO$_X$ emissions by notch for the HST MTU 16V4000R41R engine

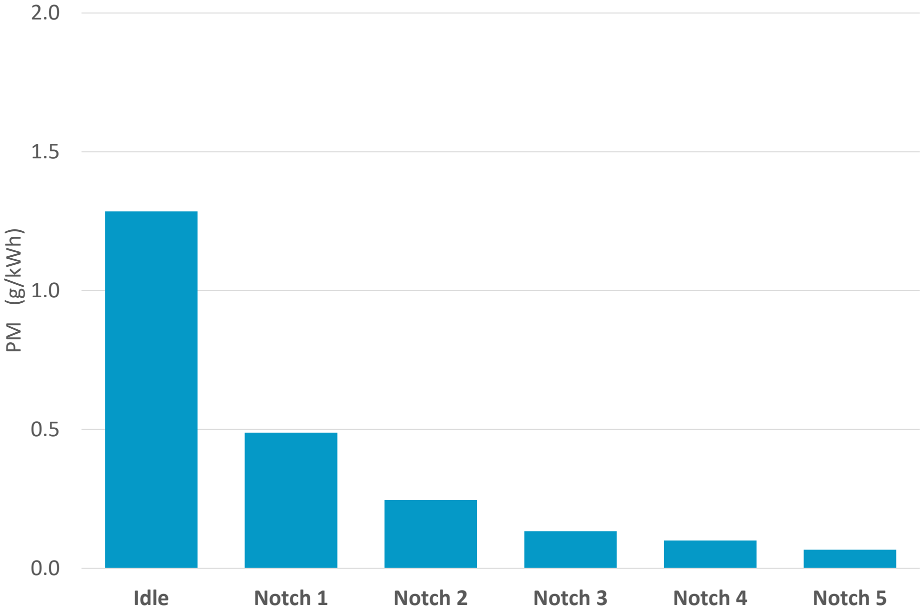


At lower power output, more of the total combustion products from engines are air pollutants. The net result of the production of vastly more NO_X per unit of useful energy in idle. Although for this engine the total mass of combustion products at Notch 5 is 7 times that at idle, 51%-60% of the drive cycle time is spent in idle so that with the 2 power cars + 4 passenger coaches the total amount of NO_X produced in Notch 5 is only 60% greater than in idle but with 2 power cars + 8 passenger coaches the total amount of NO_X produced in Notch 5 is 6 times greater than in idle.

Thus with the 2 power cars + 4 coaches 20% of the total NO_X emissions produced across the typical drive cycle are generated in idle and 36% of the total NO_X emissions are produced in Notch 5, but with the 2 power cars + 8 coaches 10% of the total NO_X emissions produced across the typical HST drive cycle are generated in idle and 60% of the total NO_X emissions are produced in Notch 5.

HST PM emissions (g/kWh) vary much more with engine notch than for NO_X with the variation in other air pollutants (apart from SO_2 which is a function of fuel sulphur levels) lying between the two extremes of NO_X and PM variation (Figure 30).

Figure 30 PM emissions by notch for the HST MTU 16V4000R41R engine



The methodology described here is applicable to all GB freight diesel locomotives since these all have electric transmission. Furthermore, extensive US emissions certification data is available for a very large majority of GB freight locomotives since these use US-built engines that are also sold in the US. The methodology is also applicable to passenger trains with electric transmission, mainly higher-speed trains e.g. HSTs, Voyagers (Classes 220 and 221), Meridians (Class 222) and IEPs (Classes 800 and 802), as well as lower-speed regional bi-mode units (Classes 755 and 769).

In all diesel electric rolling stock some energy is lost to inefficiencies in transmission (alternator inefficiency, traction electronics losses and traction motor inefficiency) and in powering auxiliary loads. (The latter includes brake system air compressors, radiator cooling fans and for passenger trains the power for 'hotel loads' such as lighting, heating, ventilation, air conditioning and sockets for passenger use (hotel loads are referred to as Electric Train Supply (ETS) for GB locomotive-hauled passenger train or auxiliary supply for GB multiple units).

Over the years transmission efficiency has improved with the use of more sophisticated and efficient electrical equipment but the minimum losses achievable (for a high power locomotive at full power) from engine to wheel are around 9% for the most modern equipment (single alternator for all power requirements, insulated-gate bipolar transistor (IGBT) based 3-phase variable voltage and speed drive (VVSD) traction electronics and 3-phase AC traction motors. With the most modern equipment there is significantly less difference in transmission efficiency between low and high-power conditions, whereas the difference was far greater with earlier traction equipment.

The oldest diesel electric locomotives in Great Britain feature DC main generators, complex electromechanical traction equipment and DC traction motors. Moving from a DC main generator to an AC alternator with the output rectified to DC and improved but still traditional traction electrics (e.g. the HST) typically leads to a 7% improvement in transmission efficiency (full power conditions). Improving the traction DC traction electrics further leads to another 3% improvement (e.g. Class 66).

Swapping to the most modern set-up of a single alternator for all power requirements, 3-phase drive traction electronics and 3-phase AC traction motors and sophisticated auxiliary load management can yield a further 6% improvement. Overall a variation of 16% could be expected under full power conditions depending on the technologies employed, with a bigger range under lower power conditions. There is a further reduction in transmission efficiency of 15% - 20% at low power compared to high power is to be expected with older technologies.

The greater overall proportion of transmission losses and auxiliary loads at lower power outputs also amplifies the higher emissions measured 'at the engine' when emission factors are produced on an 'at the wheel' basis compared to the 'at the engine' basis.

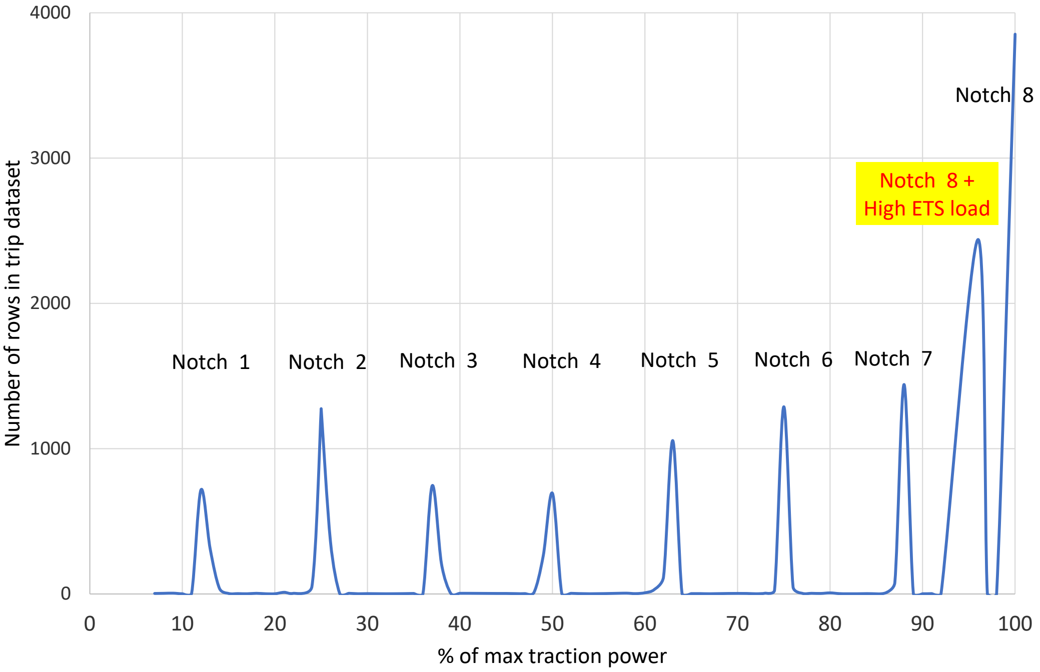
The emission factors of electric transmission locomotives prepared as part of this project are on an 'at the wheel' basis so they include the full energy cost of operation and are comparable to the hydraulic and mechanical transmissions (see Sections 7 and 8).

6.2 'Continuously variable' transmission

The most modern and more efficient 3-phase drive electronics and 3-phase AC traction motor technology discussed above has better efficiencies across the power range and also enables the power to be supplied at any level between zero and maximum rather than just at fixed notches.

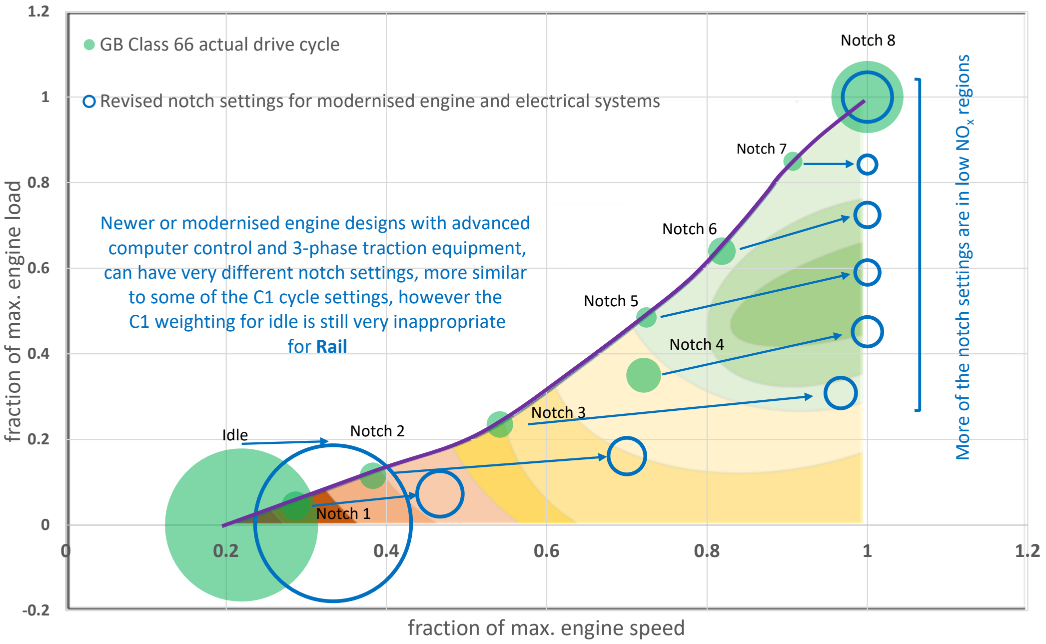
While the notch system is well understood for older diesel electric trains and locomotives, more modern trains (such as the Voyager and IET) and locomotives (such as the Class 68) have an electrical transmission described as 'continuously variable' rather than having fixed power (and brake) notches. In reality, although the power lever may have no labelling apart from min/max in some cases and can apparently be set at any level, there is more often an increased number of fixed notches available that the engine runs at rather than just Notches 0-5 or 0-8. For example, for the Voyager there are 17 notches ('0-16') in traction mode and three non-traction power modes. This situation also applies to more recent locomotives (Class 68, Class 70). With the Class 70, GE retained the traditional freight control set-up of Notches 0-8. The Vossloh/Stadler Class 68 is described as being continuously variable and apparently notch-less but analysis of Class 68 OTMR data (Figure 31) shows that power is delivered by the engine in discrete bins corresponding to Notches 0-8. It is also notable that with a high electrical train supply (ETS) load, ~100 kW of available traction power is lost in Notch 8 (96% vs 100% where 100% corresponds to maximum traction power supplied to the traction motors). Accounting for such high non-traction loads is important to accurately determine emissions at the wheel.

Figure 31 Analysis of Class 68 notch settings



As part of overall emissions reduction and engine efficiency improvements (including GHG emissions reduction), manufacturers have focused on engine design and operating strategies to spend more time in low NO_x zones as this is a simple way to both reduce emissions and to comply with the emission standards that are based on overall single emissions limit. (These changes to engine operating conditions require electronically controlled higher-pressure fuel injection systems and sophisticated computer-controlled engine management.) Consequently, newer engines with electric transmission often run at higher speeds at lower power settings than older engines (which follow a maximum power curve-based engine control strategy) do for the same power outputs; see Figure 32 . Essentially all low and medium power notch settings are moved to the right into relatively lower NO_x zones. (This approach does not apply to hydraulic or mechanical transmissions where traditional proportions of maximum power curve-based operating strategies are still used). This means some of the notch settings for newer engines are more aligned with C1/D cycle test points; however, the majority of the engine running time is still in the high NO_x area that is under represented by the C1 test cycle. This approach has been followed for newer locomotive designs (Class 68 and 70) and electrical transmission DMU designs, e.g. Voyagers and Meridians (Class 220, 221, 222) and the Intercity Express Train (IET; Class 800, 802).

Figure 32 Indicative example showing how changes to engine design and operation, along with significant changes to electrical and auxiliary systems, can result in different engine operating conditions being chosen that reduce emissions for a given power output



This approach also aligns with engine usage strategies in other applications such as in electric transmission / series hybrid vehicles, for example the TfL/Wrightbus New Bus for London (NBfL), where the engine only runs at higher power outputs at the optimum speed for efficient electrical generation which results in lower NO_x and PM emissions (thus reducing abatement requirements and ensures that more engine running time is at high exhaust temperatures needed for SCR to operate).

6.2.1 Voyager control set-up

The Voyager/Meridian family (Classes 220, 221 and 222) is an important part of the GB diesel fleet. There were no mandatory UK emissions testing requirements at the time of their construction; testing was done elsewhere in Europe on the engine design although not the variant as installed in GB trains. This could potentially mean that actual emissions could be substantially different. Furthermore, the test modes involved in such testing would not be representative of real operating conditions.

There was previously little publicly available information regarding this train family's control system. The driver's control has no marks indicating any fixed levels, apparently implying a continuously variable control system. A University of Birmingham study[84], although focused on energy usage, suggested there may be discrete engine operating points. Understanding exactly what these operating points are, how they are related to

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[84] Wang, L. (2014). *Energy efficiency for diesel passenger trains*. Masters thesis, University of Birmingham.

the control system, and how they are recorded in the OTMR would allow emissions by notch to be developed for these train classes.

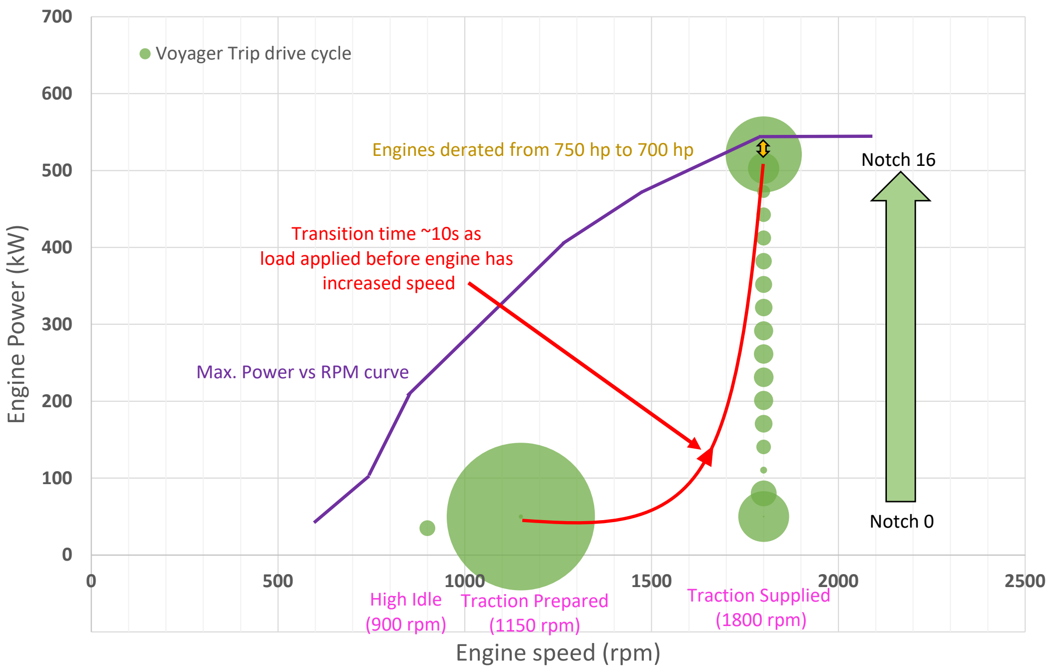
In order to better understand the engine and control set-up, as part of this project, high quality audio and GPS measurements were taken of Class 220 and 221 in passenger service. Based on these measurements the Voyager has four engine speeds:

1. 'Low Idle' (600 rpm / 30 Hz measured)
2. 'High Idle' (900 rpm / 45 Hz measured)
3. 'Traction Ready' (1150 rpm / 57.5 Hz measured) - used for most braking and coasting as well as preparing the engine to move away from stationary
4. 'Traction Power' (1800 rpm / 90 Hz measured) used for all traction current supply

These are the only engine speeds used, although there is a transition time of around 10 seconds (which is negligible across a daily drive cycle) from 3. 'Traction Ready' to 4. 'Traction Power' as the load is applied before engine has increased speed (see Figure 33). Control-wise this was an easy to implement configuration two decades ago when the Voyagers were built, especially given Alstom traction electrical equipment and the rest of the control systems produced by Bombardier.

This insight into how the Voyagers operate allows the OTMR to be interpreted to identify the engine operating conditions at any moment and thus to generate emission factors by notch.

Figure 33 Voyager trip drive cycle and engine use



6.2.2 IET control set-up

The IET is now a significant and growing part of the GB diesel fleet with further deliveries scheduled through to 2023. Most variants are bi-mode so it is important to understand its emissions when operating away from electrified parts of the network. The IET's diesel engine is Euro IIIB compliant unlike the HSTs it replaces.

Understanding the IET engine operating conditions that are used to meet particular power requirements allows the associated emissions to be estimated.

As with the Voyager, public understanding of the IET control system is limited. The system is similar but more sophisticated than the Voyagers', reflecting advances in control electronics in the last two decades. Based on detailed audio and GPS measurements in passenger service there are five engine operating speeds (+/-20 rpm):

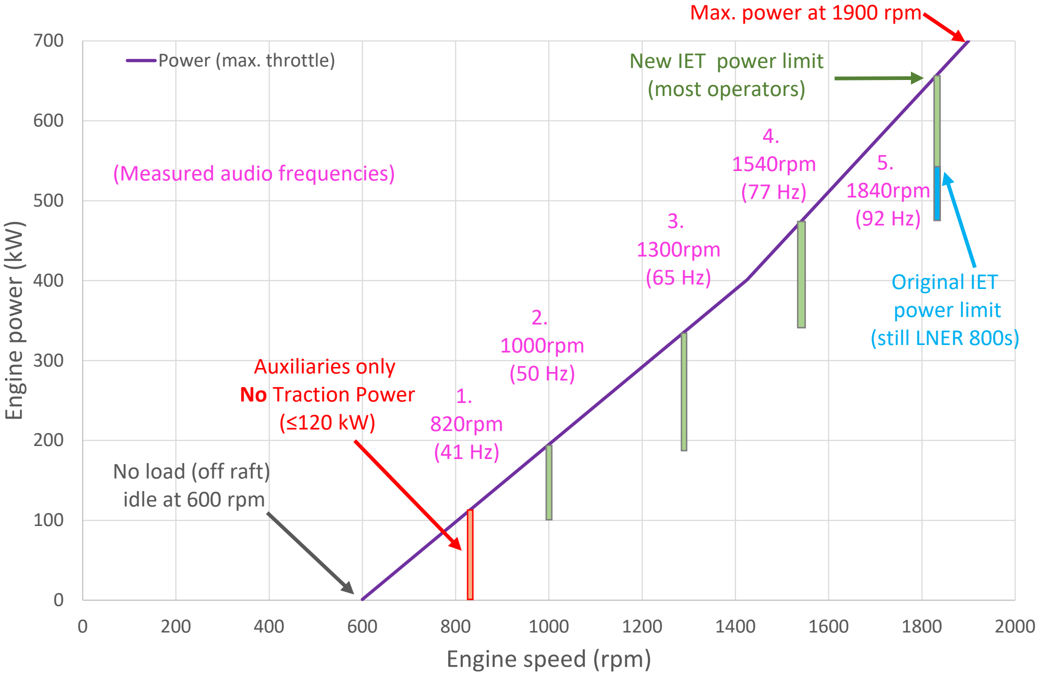
1. 820 rpm (41 Hz measured) – no Traction Power, just auxiliaries
2. 1000 rpm (50 Hz measured)
3. 1300 rpm (65 Hz measured)
4. 1540 rpm (77 Hz measured)
5. 1840 rpm (92 Hz measured)

The transition time between engine speeds is less than two seconds.

There are three engine rafts on a 5-car unit and five engine rafts on a 9-car unit. Each engine raft can provide up to 120 kW auxiliary supply, so one raft can just about supply all auxiliary requirements (heating, lighting, etc.) for a 5-car unit. All of the MTU 12V1600R80L engines used in all versions of the IET have been derated from a maximum 700 kW (940 hp) at 1900 rpm. For IETs procured under the original DfT agreement (LNER Class 800s) the engines are limited to 520 kW (700 hp) at 1840 rpm, while GWR Class 800s and all Class 802s are limited to 670 kW (900 hp) at 1840 rpm.

Combining the audio and GPS data with available information on the MTU engine, allows determination of the series of steps between the five engine speeds used to deliver the full available power range (Figure 34). These insights have enabled production of emission factors in the absence of detailed engine testing data for the specific IET real world operating modes.

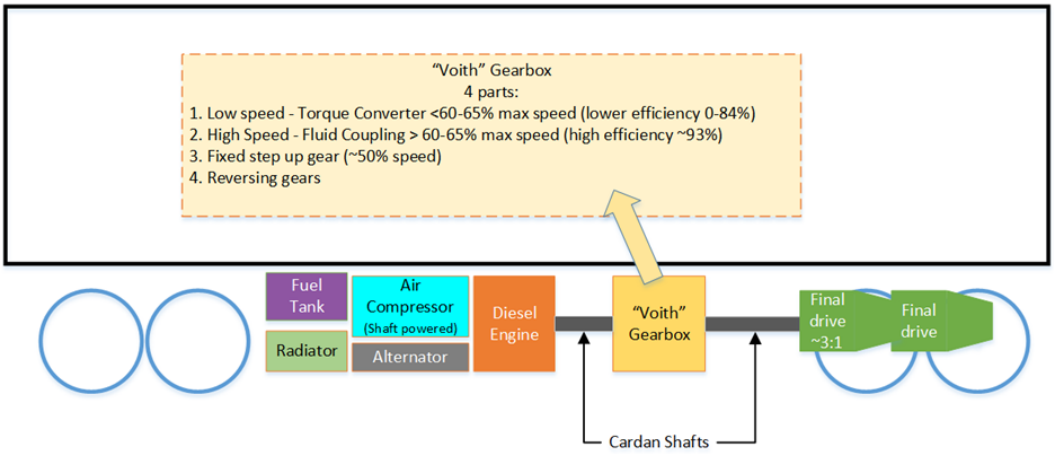
Figure 34 IET engine set-up



7 Methodological approach: Diesel hydraulic transmission

A diesel engine primarily drives a gearbox which will use a torque converter at low speed and a fluid coupling at high speed to then drive a final drive to turn the vehicle wheels. Part of the mechanical power generated drives an air compressor to maintain brake pressure and an alternator which provides electrical power for train heating and lighting as well as radiator cooling fans (see Figure 35).

Figure 35 Schematic of diesel hydraulic transmission (Class 158)

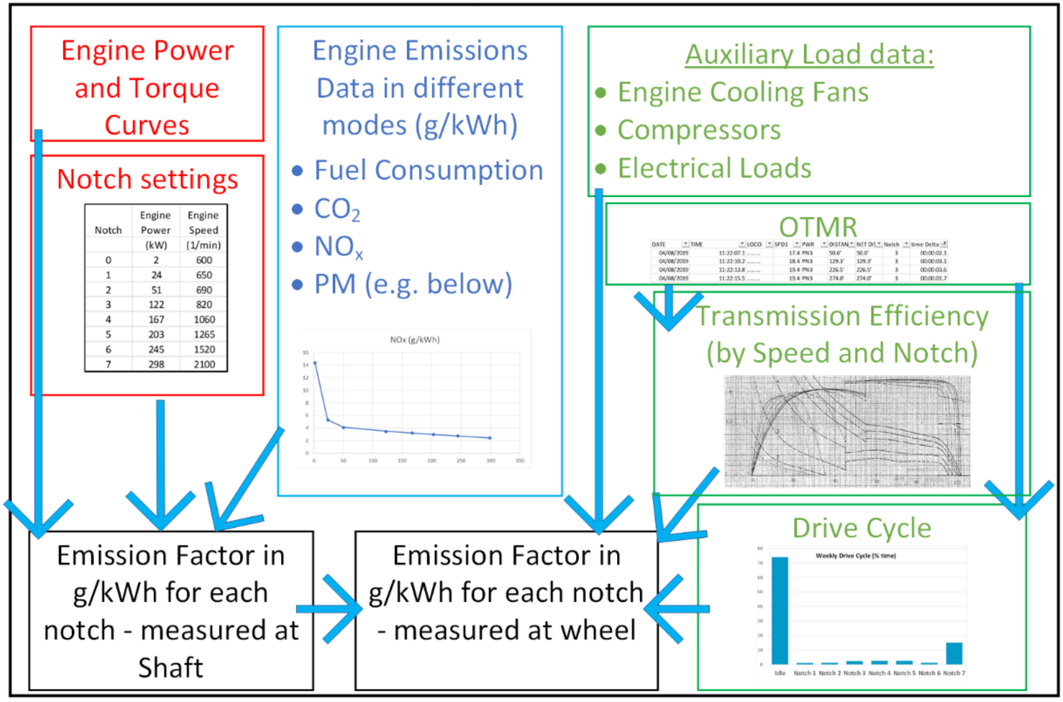


The hydraulic transmissions used in local/regional DMUs built more than a decade ago present the greatest challenge to improving emission factors as the efficiency of the transmission is highly variable and dependent on DMU speed and engine torque. Hence there is a lot of route and service variability and uncertainty. With hydraulic transmission, the engine spends a substantial quantity of time at high power and torque, so quick improvements can be made by focusing on that data with a detailed understanding of the torque converter efficiency, final drive ratio and route/service variations.

Data required to develop emission factors by notch are:

- engine data (power curves, notch setting, fuel consumption curves)
- engine emissions testing at various power outputs
- 'Voith' gearbox data (varies for class/engine/maximum unit speed)
- final drive gearbox ratio (range between 2.7 to 3.4 :1 reduction – varies depending on gearbox set up and max unit speed)
- wheel diameter
- drive cycle/OTMR data.

Figure 36 Flowchart illustrating methodology for determining emission factors by notch for diesel hydraulic transmission



Notch	Engine Power (kW)	Engine Speed (1/min)
0	2	600
1	24	650
2	51	690
3	122	820
4	167	1060
5	203	1265
6	245	1520
7	298	2100

DATE	TIME	LOCO	SPD1	PWR	DISTAN	NET DIS	Notch	time Delta
04/08/2019	11:22:07.1	....	17.4	PN3	50.6'	50.6'	3	00:00:02.1
04/08/2019	11:22:10.2	....	18.4	PN3	129.3'	129.3'	3	00:00:03.1
04/08/2019	11:22:13.8	....	19.4	PN3	226.5'	226.5'	3	00:00:03.6
04/08/2019	11:22:15.5	....	19.4	PN3	274.0'	274.0'	3	00:00:01.7

This example is for the variants of Class 158/159 with the 400 hp Cummins engine. With hydraulic transmissions the OTMR data is very important as the transmission efficiency varies significantly with train speed and this needs to be taken account of when understanding emissions measured at the wheel, especially as the transmission efficiency is very poor at low train speeds (which can align with an area of interest for local rail emissions and air quality issues).

Figure 37 NO_X emissions by notch for Class 158/159 with the Cummins 400 hp engine

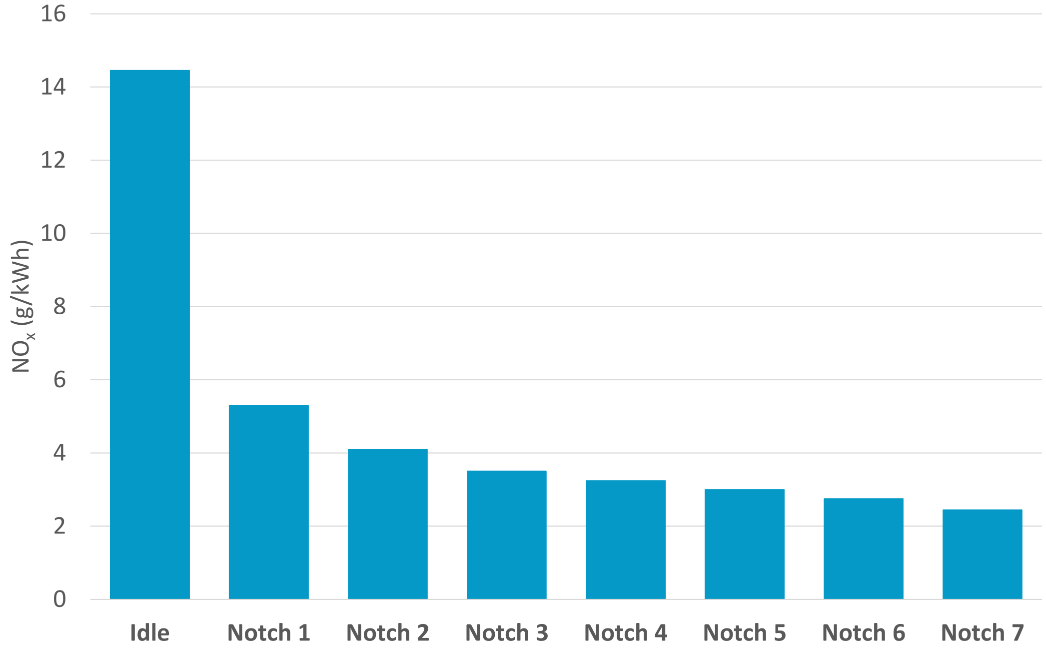
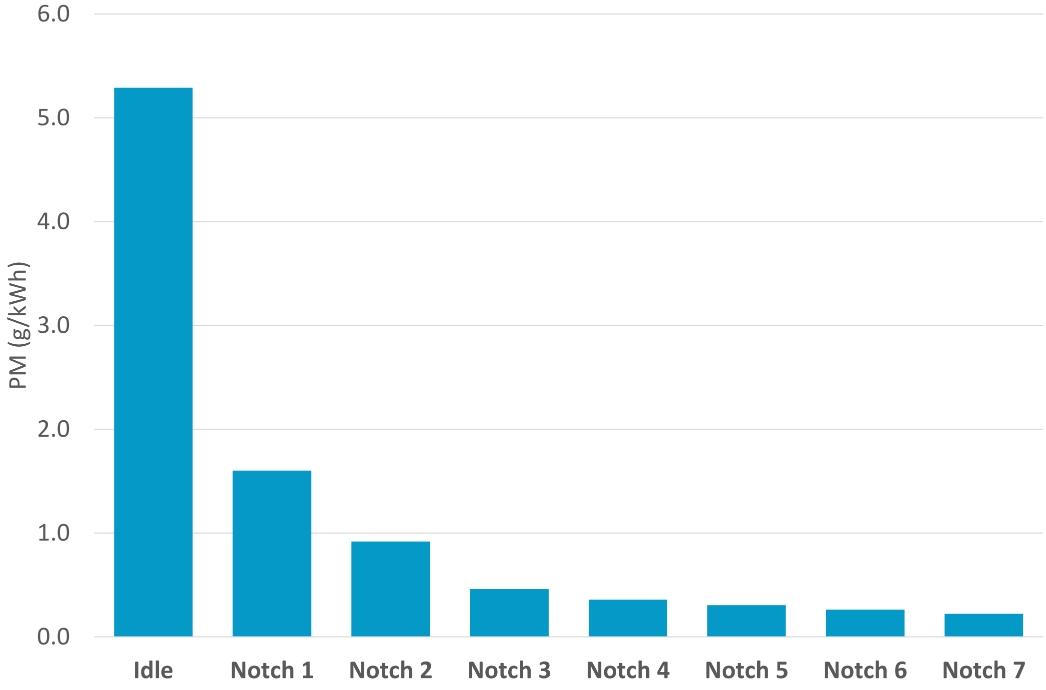


Figure 38 PM emissions by notch for Class 158/159 with the Cummins 400 hp engine



It is worth noting that a 24% reduction was seen in the PM measurements[85] (with limited testing) for this engine done in 2007 to investigate the swap to low sulphur

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[85] Silver, I. (2007). *T536: Investigation into the use of sulphur-free diesel fuel on UK railways*. RSSB.

diesel for rail in the UK in 2012 (which is within the typical 20-25% range expected when changing to ULSD).

With hydraulic transmissions, stopping drive cycles are characterised by extensive use of Idle and Notch 7 (see Figure 39) due to frequent need to accelerate away from stops, whereas limited-stop drive cycles have greater use of Notches 3-6 (see Figure 40) in order to maintain speed over longer distances between stops. A significant use of Notches 1 and 2 is needed to safely start the train on gradients.

Figure 39 Typical Class 158/159 drive cycle for a 'stopping' journey

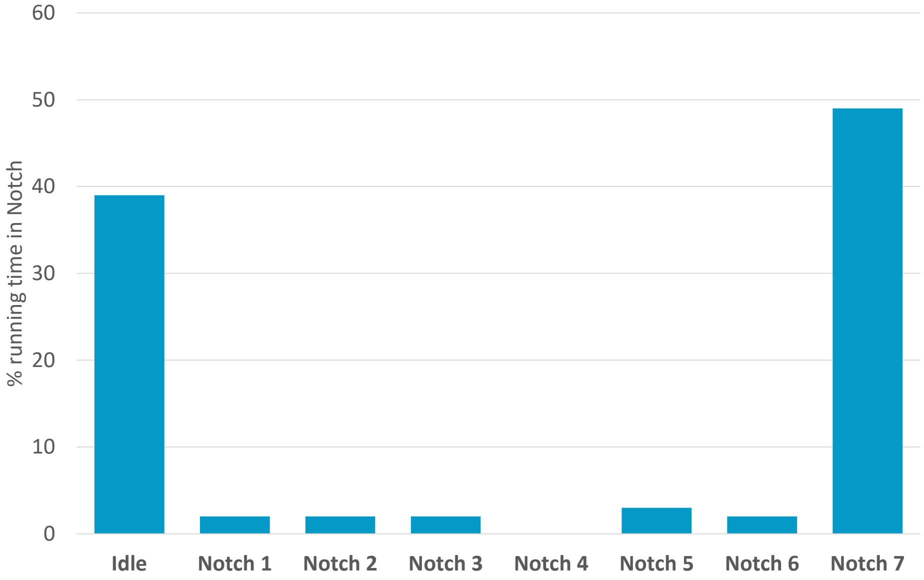


Figure 40 Typical Class 158/159 drive cycle for a 'limited-stop' journey

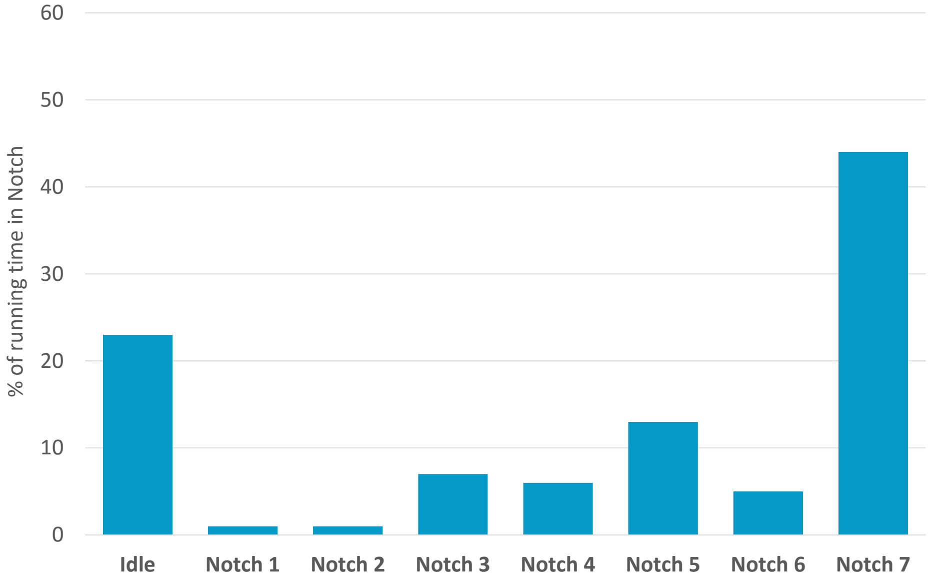
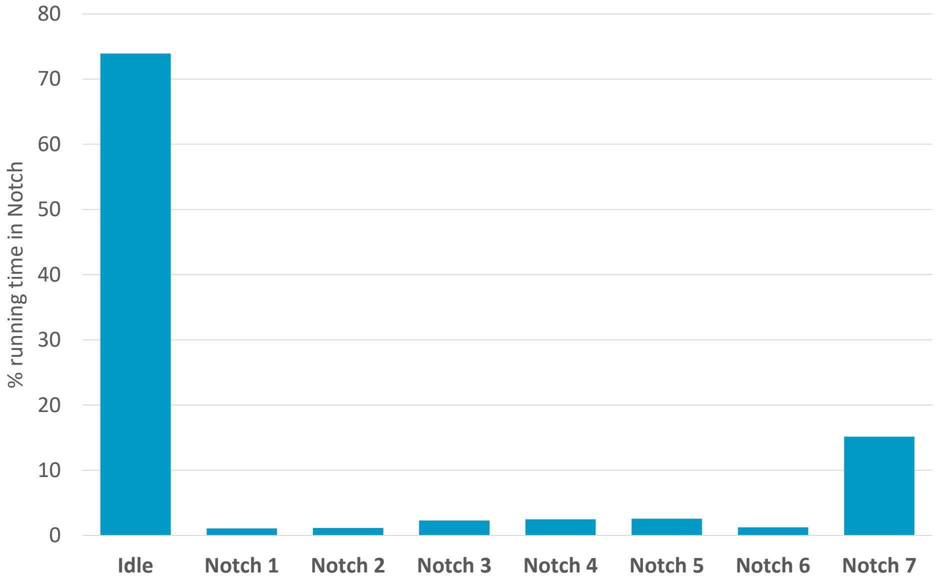


Figure 41 shows the typical weekly Class 158/159 drive cycle. Unlike the two previous trip-specific graphs this includes a lot more idling, for example while the train is 'warming up' in the morning including creating enough air pressure, time waiting at termini between journeys, and cleaning in the off-peak on some days.

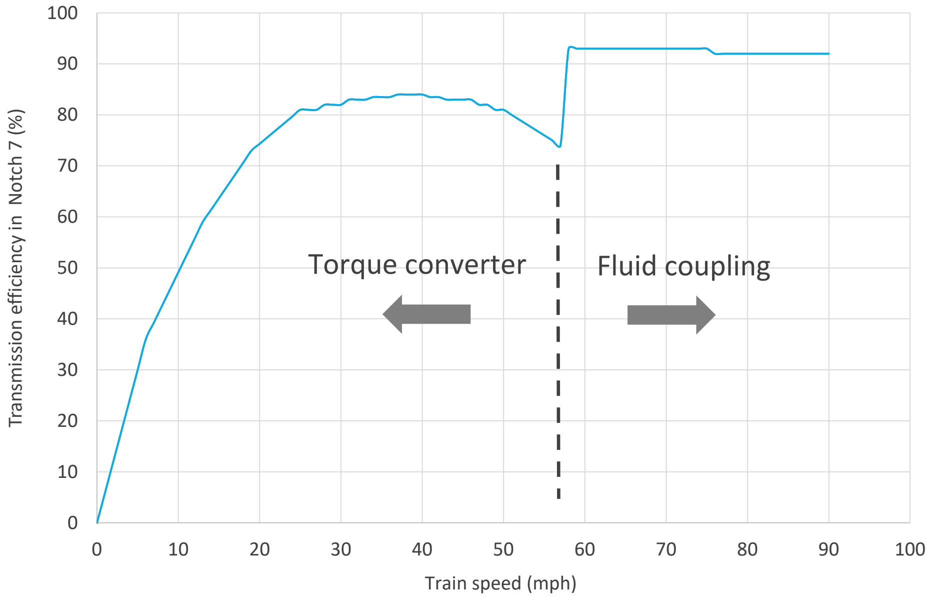
Figure 41 Typical weekly Class 158/159 drive cycle



The transmission efficiency of the 'hydraulic' drive systems varies substantially with train speed and engine notch hence detailed analysis is needed to assess transmission losses and then to use this to translate static engine emissions testing on a load cell to emissions on an 'at the wheel' basis. The very variable efficiency of the overall transmission with notch and train speed can be seen in Figure 42 below. Curves for other notches are similar shapes but with the transition speed lower and with lower efficiencies when the torque converter is operational.

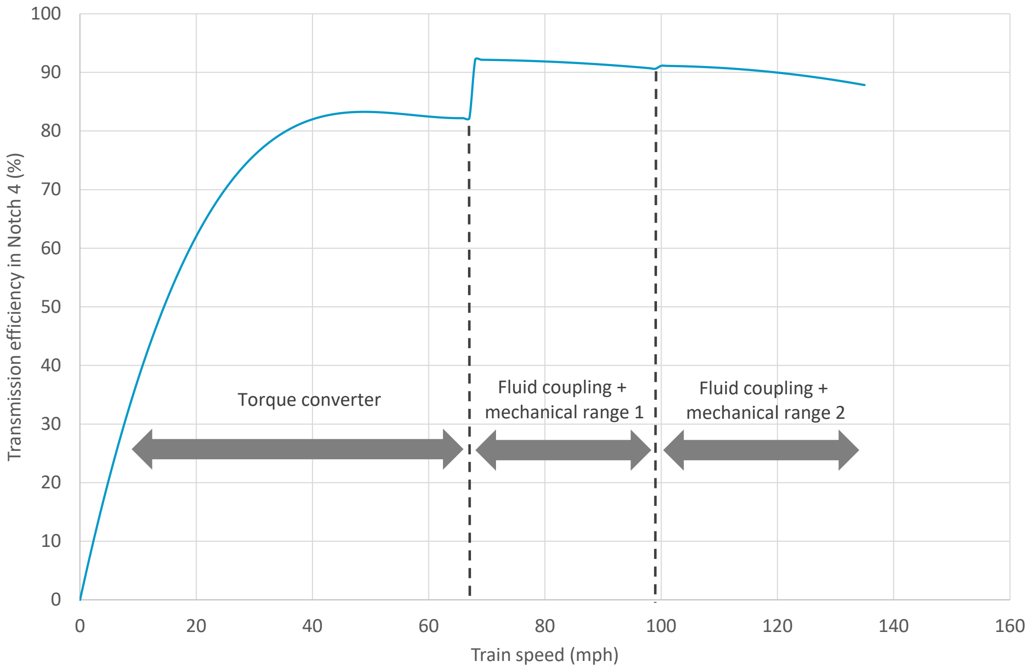
Figure 42 shows the transmission efficiency chart for the Cummins 400hp 158/159 with the engine in Notch 7 vs train speed (mph). The chart shows efficiency of the Voith T211 specific to this engine for the Class 158, Gmeinder GM190 final drive gearboxes, drive shafts and wheels. The change at around 56mph from less and variably efficient torque converter to more efficient fluid drive (that only works at high speeds and lower torques) can clearly be seen.

Figure 42 Transmission efficiency versus train speed for Class 158/159 with Cummins 400 hp engine in Notch 7



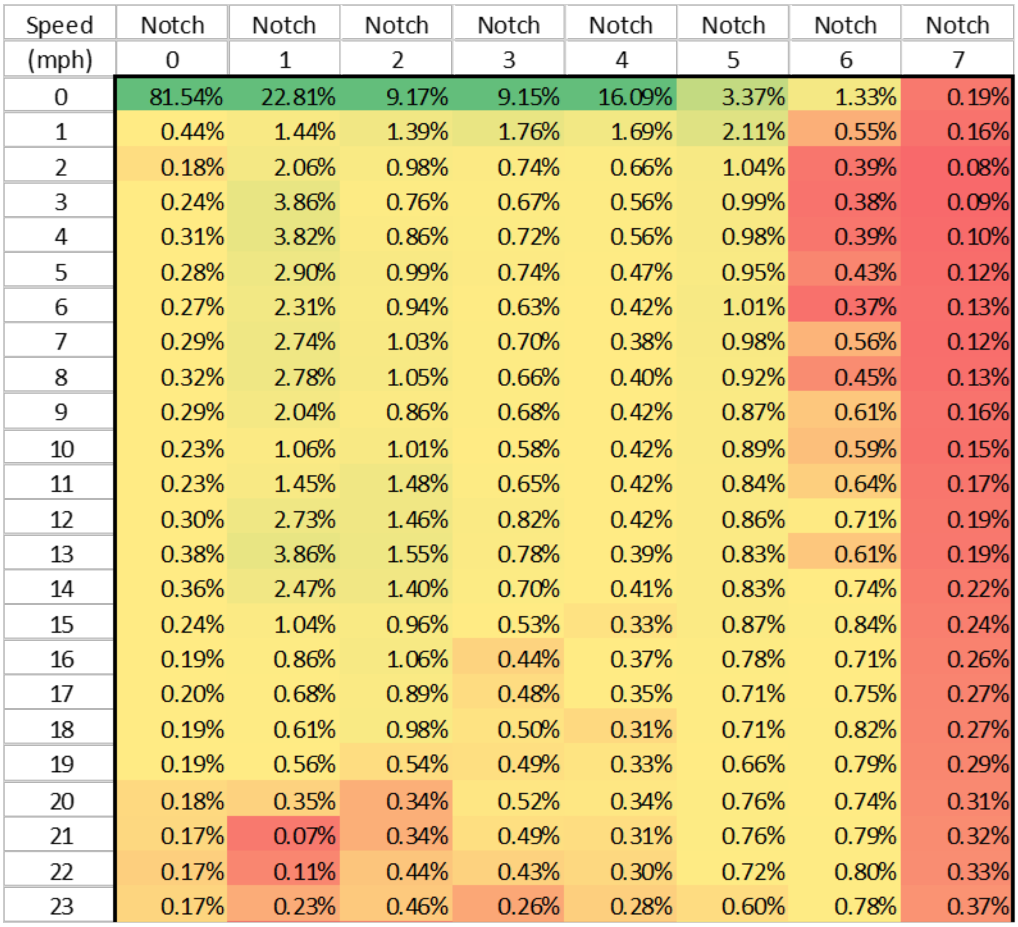
Some DMUs with more powerful engines and higher top speeds (Classes 180 and 185) also have a more complex transmission design. The Voith T312 has three ranges of which the torque converter has one range and the fluid coupling has two ranges, this is achieved with a simple 2-speed mechanical gear change used in combination with the fluid coupling. This configuration extends the operating speed range of the fluid drive (along with its high efficiency) albeit with the slight sacrifice of a minimum 3% of overall efficiency when using the fluid coupling and sees a second step in the respective efficiency vs speed chart (Figure 43).

Figure 43 Transmission efficiency versus train speed for Class 180 with Cummins 750 hp engine, 3-speed gearbox and the engine in Notch 4



The OTMR was analysed to calculate the time spent at each notch and speed combination (speed rounded to the nearest mph) and the results can be seen in Table 6 below. This was then combined with the transmission efficiency at each notch and speed to produce the weighted average transmission efficiency for each notch.

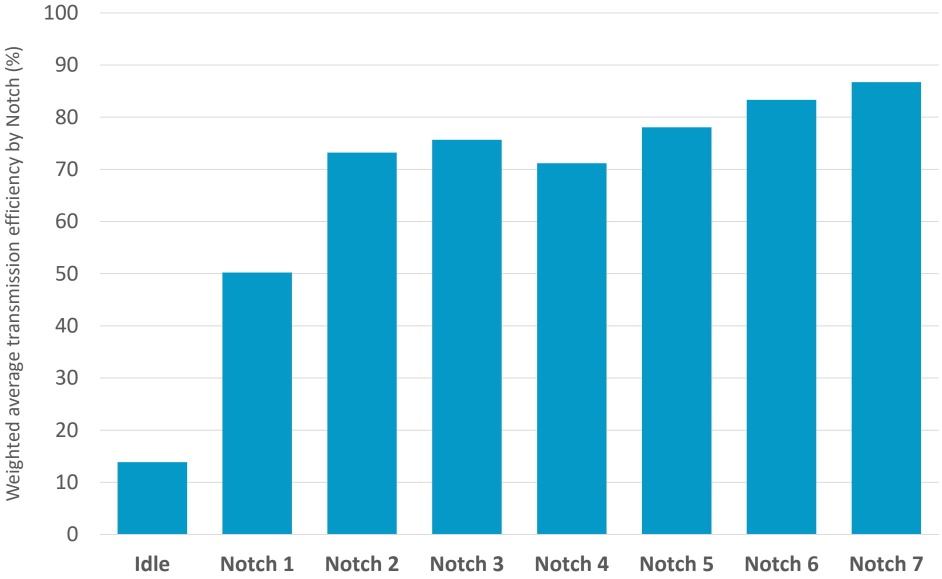
Table 6 Extract of table of Class 158/159 time spent in each notch/speed combination. Green highlighting indicates the most common speeds in each notch and red highlighting indicates the least common speeds in each notch.



Speed (mph)	Notch 0	Notch 1	Notch 2	Notch 3	Notch 4	Notch 5	Notch 6	Notch 7
0	81.54%	22.81%	9.17%	9.15%	16.09%	3.37%	1.33%	0.19%
1	0.44%	1.44%	1.39%	1.76%	1.69%	2.11%	0.55%	0.16%
2	0.18%	2.06%	0.98%	0.74%	0.66%	1.04%	0.39%	0.08%
3	0.24%	3.86%	0.76%	0.67%	0.56%	0.99%	0.38%	0.09%
4	0.31%	3.82%	0.86%	0.72%	0.56%	0.98%	0.39%	0.10%
5	0.28%	2.90%	0.99%	0.74%	0.47%	0.95%	0.43%	0.12%
6	0.27%	2.31%	0.94%	0.63%	0.42%	1.01%	0.37%	0.13%
7	0.29%	2.74%	1.03%	0.70%	0.38%	0.98%	0.56%	0.12%
8	0.32%	2.78%	1.05%	0.66%	0.40%	0.92%	0.45%	0.13%
9	0.29%	2.04%	0.86%	0.68%	0.42%	0.87%	0.61%	0.16%
10	0.23%	1.06%	1.01%	0.58%	0.42%	0.89%	0.59%	0.15%
11	0.23%	1.45%	1.48%	0.65%	0.42%	0.84%	0.64%	0.17%
12	0.30%	2.73%	1.46%	0.82%	0.42%	0.86%	0.71%	0.19%
13	0.38%	3.86%	1.55%	0.78%	0.39%	0.83%	0.61%	0.19%
14	0.36%	2.47%	1.40%	0.70%	0.41%	0.83%	0.74%	0.22%
15	0.24%	1.04%	0.96%	0.53%	0.33%	0.87%	0.84%	0.24%
16	0.19%	0.86%	1.06%	0.44%	0.37%	0.78%	0.71%	0.26%
17	0.20%	0.68%	0.89%	0.48%	0.35%	0.71%	0.75%	0.27%
18	0.19%	0.61%	0.98%	0.50%	0.31%	0.71%	0.82%	0.27%
19	0.19%	0.56%	0.54%	0.49%	0.33%	0.66%	0.79%	0.29%
20	0.18%	0.35%	0.34%	0.52%	0.34%	0.76%	0.74%	0.31%
21	0.17%	0.07%	0.34%	0.49%	0.31%	0.76%	0.79%	0.32%
22	0.17%	0.11%	0.44%	0.43%	0.30%	0.72%	0.80%	0.33%
23	0.17%	0.23%	0.46%	0.26%	0.28%	0.60%	0.78%	0.37%

The very variable efficiency of the transmission with notch (the curves for other notches are similar shapes) and speed is seen in the chart below.

Figure 44 Weighted average transmission efficiency in each notch for Class 158/159 while in motion



This was then combined with data for the time spent in idle with the transmission disengaged and with emissions data at the engine (as seen in Figure 45 for NO_X and Figure 46 for PM) to enable the emissions at the wheel to be calculated. The behaviour for NO_X and PM differs. For NO_X, while the total production is higher at high engine power outputs the total NO_X production at Notch 7 is only around 8 times that at idle, far less than one would expect from the fuel usage difference and the significant NO_X production in idle. However, for PM the total production does not vary significantly with engine power output, so at a high level what matters is just if the engine is running (versus not).

Figure 45 Total NO_X emissions per hour in each notch at the engine and at the wheel after including transmission and auxiliary losses for Class 158/159 with the Cummins 400 hp engine

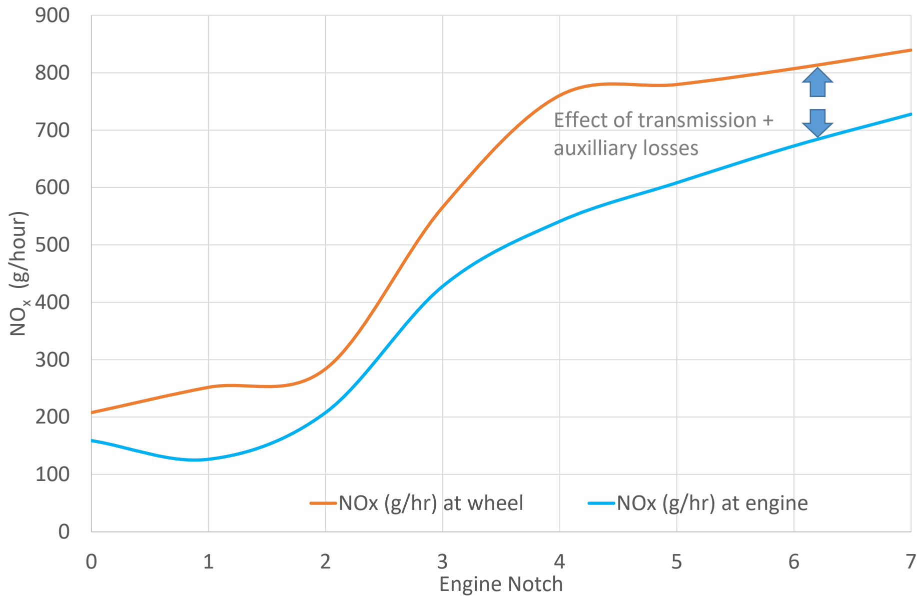
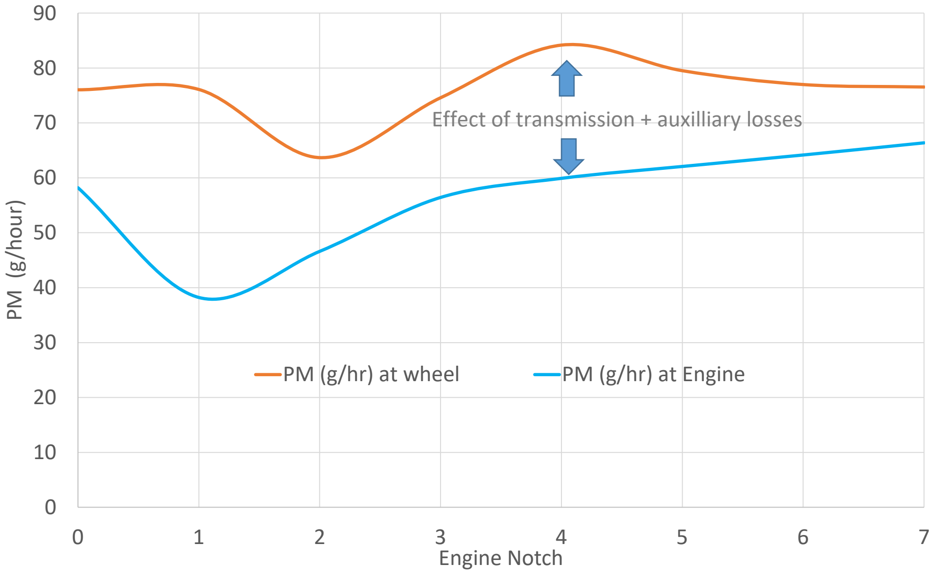


Figure 46 Total PM emissions per hour in each notch at the engine and at the wheel after including transmission and auxiliary losses for Class 158/159 with the Cummins 400 hp engine



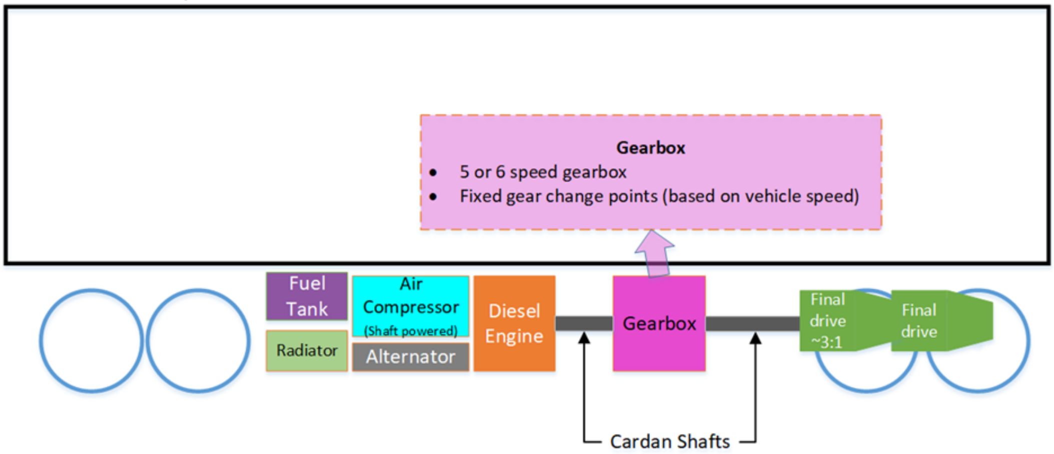
8 Methodological approach: diesel mechanical transmission

The recent trend has been for new regional/local DMUs to be fitted with mechanical transmission to improve fuel efficiency and performance on services with lots of stops, where far more time is spent at lower speeds. OTMR data from these units can be combined with detailed technical data from the manufacturer to enable better emission factors to be obtained. With mechanical transmission, the data and understanding will have good transferability between routes.

A diesel engine primarily drives a gearbox with 6 or 7 speeds and fixed gear change points and then in the same way as hydraulic transmissions drive a final drive gearbox to turn the vehicle wheels. The lowest 'gear' in the gearbox is always a torque convertor but unlike the hydraulic case it is only used between 0 and 20 mph in the Class 172 case (or 15 mph in the case of the new CAF Class 195/196) and is much better optimised to a smaller operating range at low speeds than in the hydraulic case. Above 20 mph the 5 (Class 172) or 6 (Class 195/196) fixed mechanical gear ratios are used. Some mechanical gearboxes have the ability to select neutral and hence allow coasting (e.g. Class 195/196) where as others do not have a neutral option (e.g. Class 172) so do not allow coasting which can increase fuel consumption and emissions, negating some but not all of the benefits of using mechanical transmissions over hydraulic ones.

Part of the mechanical power generated drives an air compressor to maintain brake pressure and an alternator which provides electrical power for train heating and lighting as well as radiator cooling fans (see Figure 47).

Figure 47 Schematic of diesel mechanical transmission

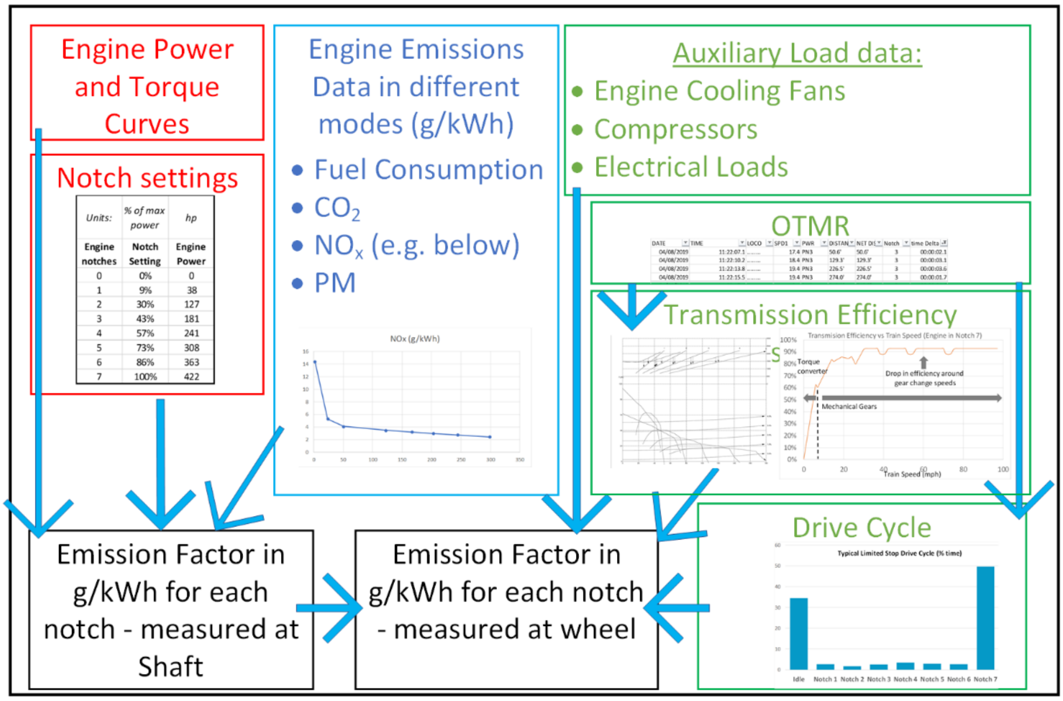


Data required to develop emission factors by notch are:

- engine data (power curves, notch setting, fuel consumption curves)
- engine emissions testing at various power outputs
- gearbox data (varies for class/engine/maximum unit speed)

- final drive gearbox ratio (varies depending on gearbox set up and maximum unit speed)
- wheel diameter
- drive cycle/OTMR data.

Figure 48 Flowchart illustrating methodology for determining emission factors by notch for diesel mechanical transmission



Units:	*% of max power*	*hp*
Engine notches	**Notch Setting**	**Engine Power**
0	0%	0
1	9%	38
2	30%	127
3	43%	181
4	57%	241
5	73%	308
6	86%	363
7	100%	422

Figure 49 NO_X emissions by notch for Class 172 at the engine

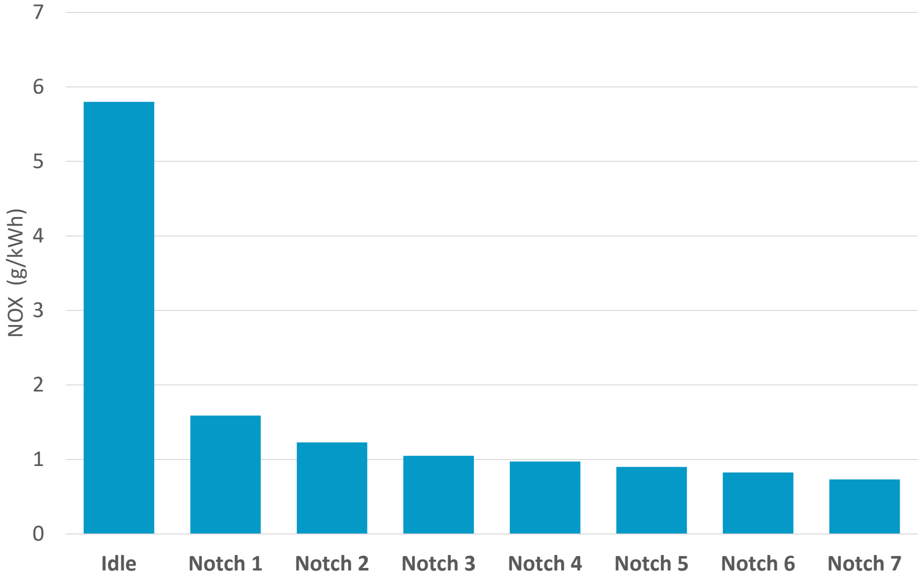


Figure 50 PM emissions by notch for Class 172 at the engine

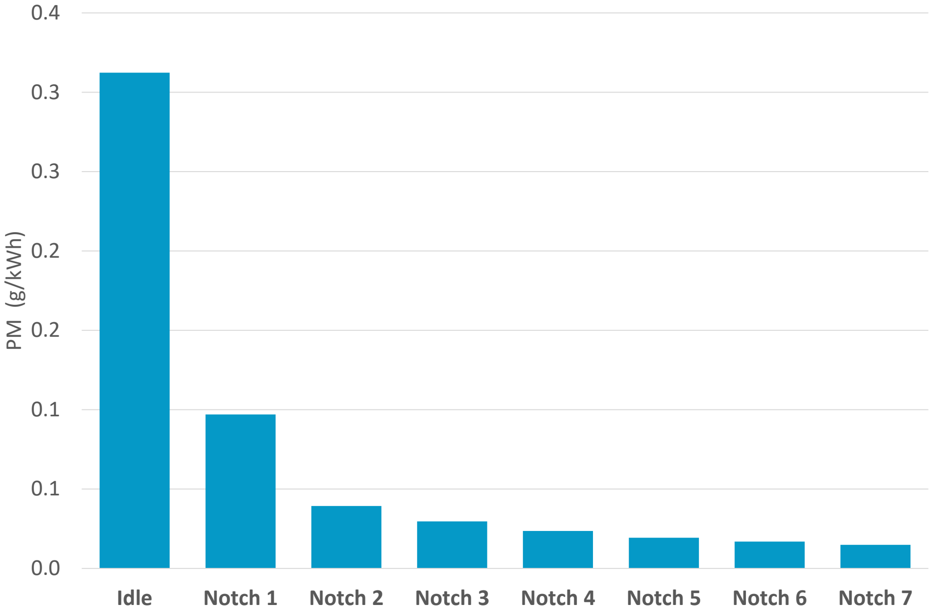


Table 7 Gear ratios, final drive ratio and the fixed train speeds at which the Class 172 gearbox automatically changes gear (assuming half worn wheels)

	Change down point (mph)	**Change up point (mph)**	**Gear ratio**	**Final drive ratio**
Torque Converter	0 *	20.5	-	2.22
1	17.4	26.8	2.81	
2	25.5	41.1	1.84	
3	39.2	55.4	1.36	
4	52.9	75.3	1.00	
5	73.4	104.5 **	0.80	

*Min speed, ** Max Speed

The transmission efficiency of the mechanical drive systems varies less with train speed and engine notch than hydraulic drive systems but some detailed analysis is needed to assess transmission losses. Although these losses are smaller than for hydraulic drive systems, they are not constant and this information is used to translate static engine emissions testing on a load cell to emissions on an 'at the wheel' basis. The very variable efficiency of the overall transmission with train speed can be seen in Figure 51 below. The reduction in transmission efficiency around the gear change points can be clearly seen as each gear ratio is furthest from its optimal efficiency.

Figure 51 Transmission efficiency versus train speed for Class 172

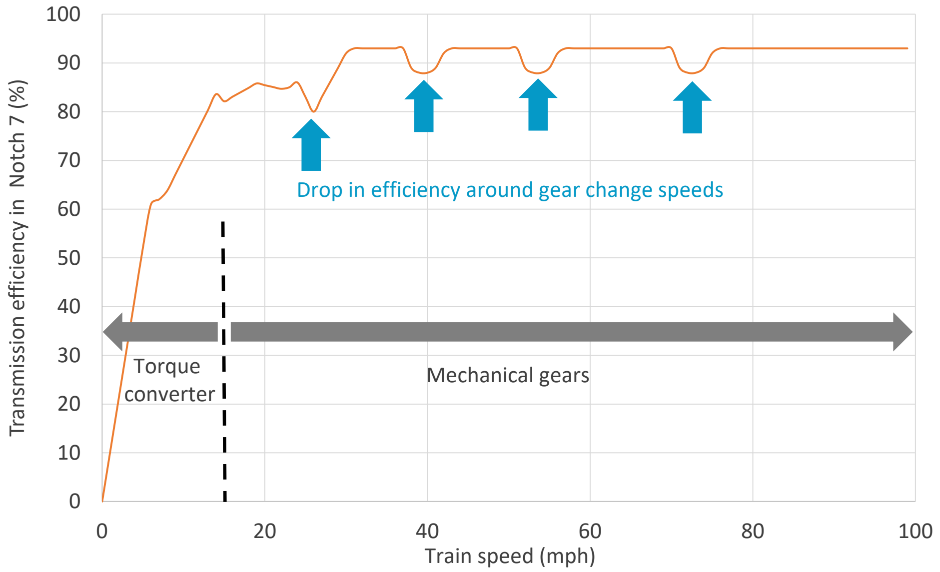


Figure 52 shows a typical Class 172 drive cycle for a 'limited-stop' journey. Note the increase in Notch 7 and Idle and reduced use of notches in between versus the comparable hydraulic example (Figure 40). This drive cycle shows more similarity to the hydraulic stopping service drive cycle.

Figure 52 Typical Class 172 drive cycle for a 'limited-stop' journey

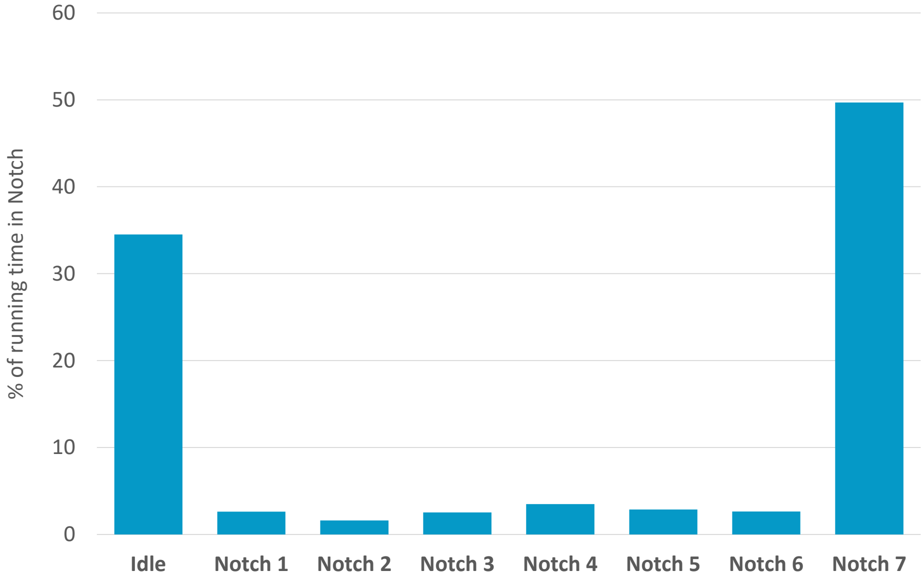
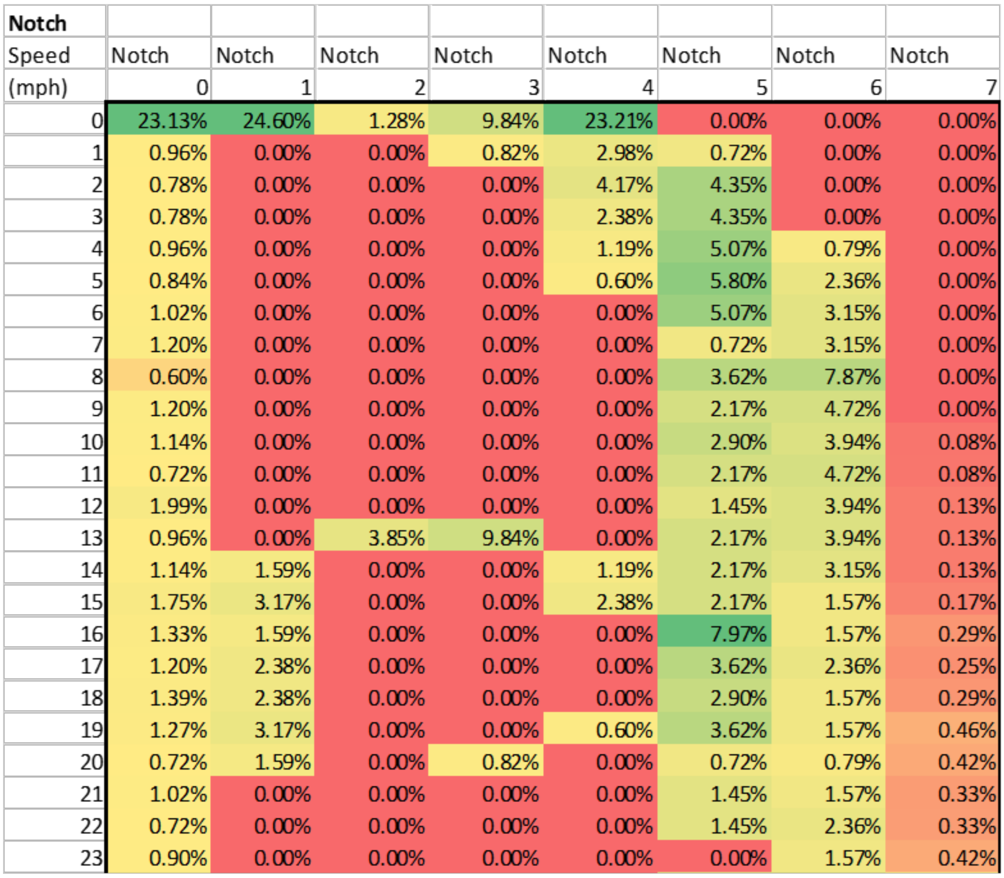


Table 8 shows time spent in each notch/speed combination for the Class 172. Note that there are far fewer notch speed combinations compared to the hydraulic transmission example (Table 6). There is negligible use of Notch 7 at low speed when the comparatively low efficiency torque converter is engaged, with initial pulling away from stationary in Notch 4 then shifting to Notch 5/6.

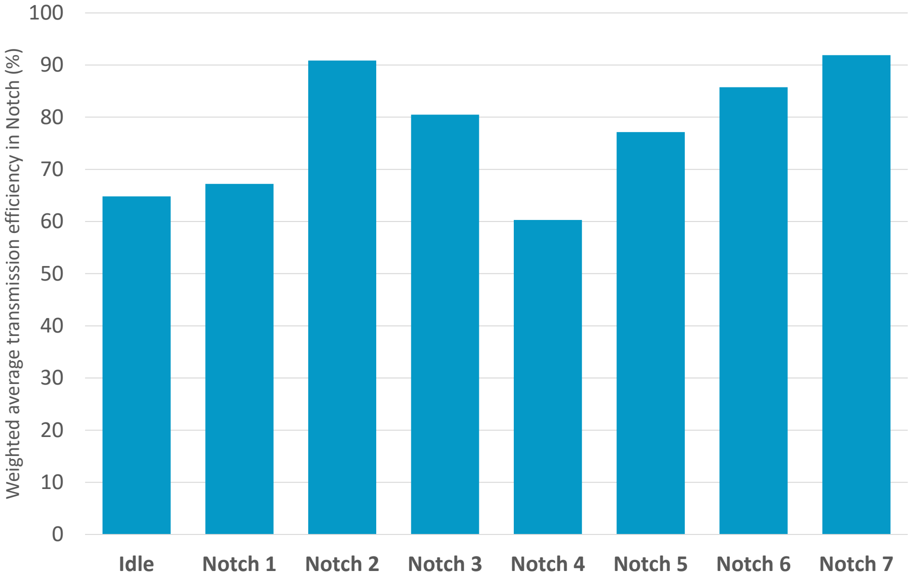
Table 8 Extract of table of Class 172 time spent in each notch/speed combination. Green highlighting indicates the most common speeds in each notch and red highlighting indicates the least common speeds in each notch.



Notch								
Speed	Notch	Notch	Notch	Notch	Notch	Notch	Notch	Notch
(mph)	0	1	2	3	4	5	6	7
0	23.13%	24.60%	1.28%	9.84%	23.21%	0.00%	0.00%	0.00%
1	0.96%	0.00%	0.00%	0.82%	2.98%	0.72%	0.00%	0.00%
2	0.78%	0.00%	0.00%	0.00%	4.17%	4.35%	0.00%	0.00%
3	0.78%	0.00%	0.00%	0.00%	2.38%	4.35%	0.00%	0.00%
4	0.96%	0.00%	0.00%	0.00%	1.19%	5.07%	0.79%	0.00%
5	0.84%	0.00%	0.00%	0.00%	0.60%	5.80%	2.36%	0.00%
6	1.02%	0.00%	0.00%	0.00%	0.00%	5.07%	3.15%	0.00%
7	1.20%	0.00%	0.00%	0.00%	0.00%	0.72%	3.15%	0.00%
8	0.60%	0.00%	0.00%	0.00%	0.00%	3.62%	7.87%	0.00%
9	1.20%	0.00%	0.00%	0.00%	0.00%	2.17%	4.72%	0.00%
10	1.14%	0.00%	0.00%	0.00%	0.00%	2.90%	3.94%	0.08%
11	0.72%	0.00%	0.00%	0.00%	0.00%	2.17%	4.72%	0.08%
12	1.99%	0.00%	0.00%	0.00%	0.00%	1.45%	3.94%	0.13%
13	0.96%	0.00%	3.85%	9.84%	0.00%	2.17%	3.94%	0.13%
14	1.14%	1.59%	0.00%	0.00%	1.19%	2.17%	3.15%	0.13%
15	1.75%	3.17%	0.00%	0.00%	2.38%	2.17%	1.57%	0.17%
16	1.33%	1.59%	0.00%	0.00%	0.00%	7.97%	1.57%	0.29%
17	1.20%	2.38%	0.00%	0.00%	0.00%	3.62%	2.36%	0.25%
18	1.39%	2.38%	0.00%	0.00%	0.00%	2.90%	1.57%	0.29%
19	1.27%	3.17%	0.00%	0.00%	0.60%	3.62%	1.57%	0.46%
20	0.72%	1.59%	0.00%	0.82%	0.00%	0.72%	0.79%	0.42%
21	1.02%	0.00%	0.00%	0.00%	0.00%	1.45%	1.57%	0.33%
22	0.72%	0.00%	0.00%	0.00%	0.00%	1.45%	2.36%	0.33%
23	0.90%	0.00%	0.00%	0.00%	0.00%	0.00%	1.57%	0.42%

The very variable efficiency of the transmission with notch (the curves for other notches are similar shapes) and speed is seen in Figure 53 below. Note the comparatively low weighted efficiency in Notch 4 as this notch is used for pulling away from stationary to 5 mph with the less efficient torque converter part of the transmission being used, which can also be seen in Table 7 above.

Figure 53 Weighted average transmission efficiency in each notch while in motion for Class 172



The weighted average transmission efficiency was then combined with emissions data at the engine (as seen in Figure 54 for NO_X and Figure 55 for PM) to enable the emissions at the wheel to be calculated. The behaviour for NO_X and PM differs. For NO_X, while the total production is higher at high engine power outputs the total NO_X production at Notch 7 is only around 3.5 times that at idle (half the relative difference seen in the hydraulic example), far less than one would expect from the fuel usage difference and the significant NO_X production in idle. However, for PM emissions the total PM production does not vary significantly with engine power output, so at a high level what matters is just if the engine is running (versus not) but the 'Notch 4' effect with low transmission efficiency can be seen in the at wheel estimates in Figure 54 and Figure 55.

Figure 54 Total NO_X emissions per hour in each notch at the engine and at the wheel after including transmission and auxiliary losses for Class 172

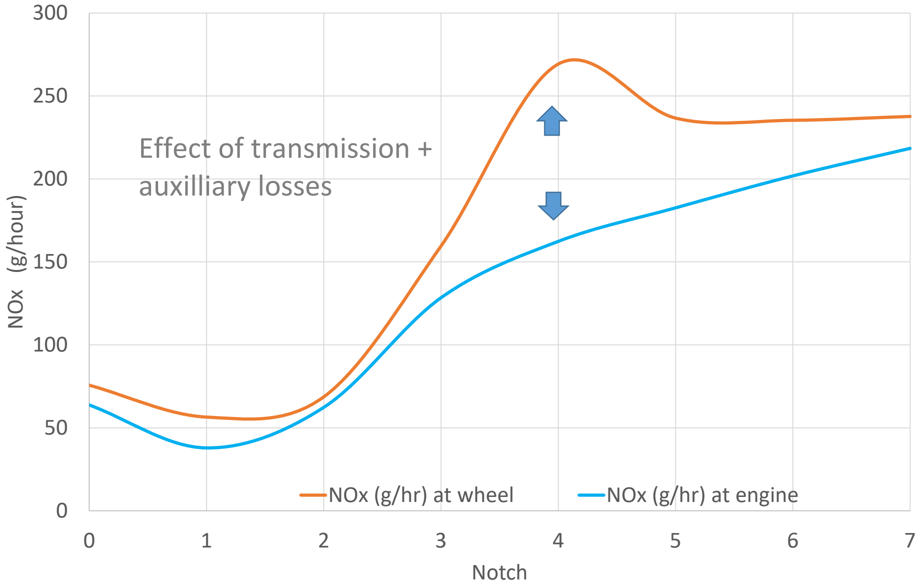
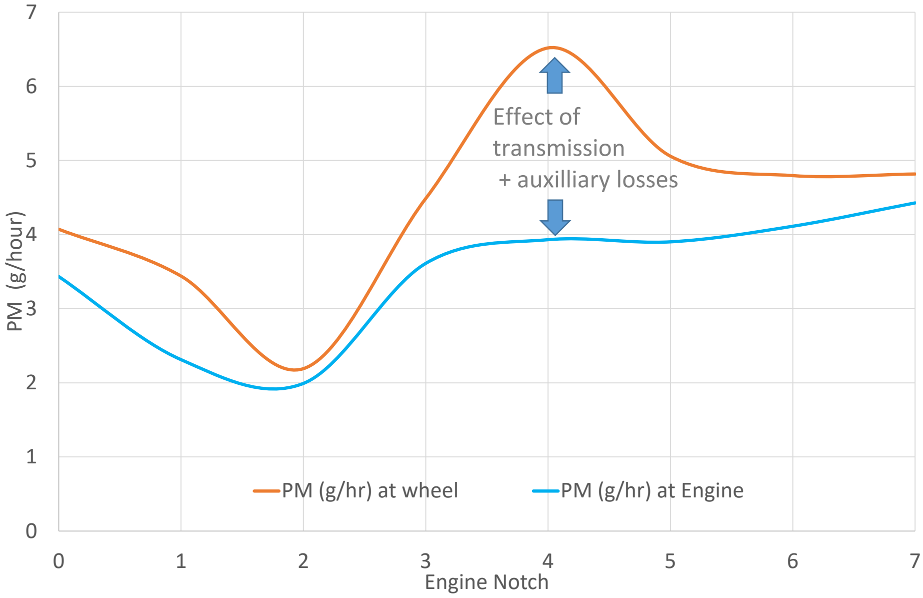


Figure 55 Total PM emissions per hour in each notch at the engine and at the wheel after including transmission and auxiliary losses for Class 172



9 Data compilation and assessment

This section describes the scope and key characteristics of the data compiled for this project. A key goal of the project was to develop factors for all of the main GB diesel fleet, which entailed using reasonably representative proxies in some instances.

9.1 Scope

Emission factors were developed for all major locomotive and train classes that are currently in service:

- Sprinters (Classes 150, 153, 155, 156)
- Express Sprinters (Classes 158, 159)
- Network Turbos (Classes 165, 166)
- Turbostars - Hydraulic transmission (Classes 168, 170, 171)
- Turbostars - Mechanical transmission (Class 172)
- Civity (Classes 195, 196)
- Voyager/Meridians (Classes 220, 221, 222)
- Flirt (Class 755)
- IET (Classes 800, 802)
- HST (Class 43)
- Classes 57, 59, 60, 66 67, 68.

These are the most common locomotive and rolling stock types covering ~85% of current passenger diesel mileage and ~95% of freight diesel mileage in 2018. Emission factors for Classes 69 and 769 were not developed as these have not yet entered revenue service.

This study excluded:

- rolling stock with less than five years remaining service life (for example Pacer DMUs, i.e. Classes 142, 143 and 144)
- less common types that form an insignificant proportion of the total fleet and /or operate very low mileages, for example Classes 20, 47 56 (more half of the remaining Class 56 are being re-engined and will become Class 69s)
- locomotives in storage
- non diesel-powered rail traction
- on-track machines (‘yellow machines’)
- stationary diesel-powered generators.

9.1.1 Analysis of diesel usage by fleet

In order to identify the most important locomotives and rolling stock classes for which emission factors needed to be developed for this study or else understand the implications of using proxy data when necessary, an analysis of current diesel usage by class was carried out based on the diesel consumption and vehicle-km data used in the 2018 NAEI. A baseline of 2018 was used, reflecting partial deployment of IETs on the Great Western Mainline (GWML).

Until recently just over 70% of the diesel fuel consumed by rail was used for passenger services but this is expected to significantly decrease as electrification and new rolling stock (both electric and bi-mode) continue to be delivered during the next few years (including for recently started franchises such as East Midlands Railway and Avanti). Consequently, diesel fuel consumption is expected to be split almost evenly between passenger and freight in five years' time.

A future scenario was therefore also considered which accounts for future deployment plans of new rolling stock that replaces and expands existing fleets. This includes the larger fleet sizes of IETs on the GWML and East Coast Mainline (ECML) which will lead to significantly reduced diesel consumption as these trains travel on electrified track (e.g., a reduction in 400 miles of diesel haulage per trip for London to Aberdeen or Inverness as IETs have now replaced HSTs). Other changes that are taken into consideration include electrification projects in the Liverpool and Manchester areas and in Scotland, as well as the deployment of bi-mode trains on the Midland Mainline (MML) by 2023. Diesel use percentages for 2018 and current and future numbers of vehicles by class are given in the Table 1 .

9.2 Fleet characteristics

A database was developed for this project for the GB passenger and freight rolling stock fleets. It includes confirmed orders out to 2023 (where the shape of the future fleet is known). The number of engines and transmission type - electric, hydraulic or mechanical (with all engine/gearbox/final drive combinations) - were identified for each unit. An overview of the database (covering number of units, engines and coaches for each class, plus future orders) is shown in Table 9. Subsequent tables below cover specific aspects such as engine model by train class, transmission type and final drive by train class, engine by applicable emission standard, quality of available emission testing data, and compiled OTMR data.

Table 9 Overview of current and future GB passenger train and freight locomotive fleets

Type	Class	No. units/ locomotives (total)	No. engines (total)	No. units/ locomotives (passenger use)	No. engines (passenger use)	No. passenger coaches per unit	% by diesel use (2018)	% by diesel use (2018)	# Future passenger cars	% Future by # cars	% Future by # cars
Diesel hydraulic/ mechanial multiple unit	142	93	186	93	186	2	2.0	3.2			
	143	21	42	21	42	2	0.4				
	144	23	56	23	56	2	0.8				
	150	136	275	136	275	2.03	2.9	6.9	276	4.8	10
	153	70	70	70	70	1	0.9		70	1.2	
	155	7	14	7	14	2	0.2		14	0.2	
	156	114	228	114	228	2	2.9		228	4.0	
	158	124	269	124	269	2.2	6	12.1	269	4.7	12
	158	9	18	9	18	2			18	0.3	
	158	47	94	47	94	2			94	1.7	
	159	22	66	22	66	3	1.9		66	1.2	
	159	8	24	8	24	3			24	0.4	
	165	39	89	39	89	2.28	3.9		89	1.6	
	165	36	88	36	88	2.44			88	1.5	
	166	21	63	21	63	3	0.3		63	1.1	
	168	28	85	28	85	3.04	2.0	6.2	85	1.5	11
	170	180	506	180	506	2.81	3.4		506	8.9	
	171	20	56	20	56	2.8	0.8		56	1.0	
	172	27	69	27	69	2.55	2	2	69	1.2	2
	172	12	24	12	24	2			24	0.4	
	175	27	70	27	70	2.59	1.8	1.8	70	1.2	1
	180	14	70	14	70	5	1.1	1.1	70	1.2	1
	185	51	153	51	153	3	3.1	3.1	153	2.7	3
	195	58	149	58	149	2.56			148	2.6	7
	196	26	80	26	80	3.07			80	1.4	
	TfW CAF	77	180	77	180	2.33			179	3.2	
Diesel electrical multiple unit	220	34	136	34	136	4	3.7	13.8	136	2.4	8
	221	44	196	44	196	4.45	6.0		196	3.4	
	222	27	143	27	143	5.3	4.1		143	2.5	
	230	8	16	8	16	2.5			20	0.4	0.4
	755/3	14	28	14	28	3			42	0.7	5
	755/4	24	96	24	96	4			96	1.7	
	TfW Bimode 4	11	44	11	44	4			44	0.8	
	TfW Trimode 4	17	68	17	68	4			68	1.2	
	TfW Trimode 3	7	14	7	14	3			21	0.4	
	769	38	76	38	76	4			152	2.7	3
	800/0	36	180	36	180	9	3.2[1]	3.2[1]	324	5.7	22
	800/1	13	65	13	65	9			117	2.1	
	800/2	10	30	10	30	5			50	0.9	
	800/3	21	105	21	105	9			189	3.3	
	802/0	22	66	22	66	5			110	1.9	
	802/1	14	70	14	70	9			126	2.2	
	802/2	19	57	19	57	5			95	1.7	
	802/3	5	15	5	15	5			25	0.4	
	80x	13	39	13	39	5			65	1.1	
	810	33	132	33	132	5			165	2.9	
Locomotives / power cars - electric transmission	HST ongoing	85	85	85	85	7.5	19.8	19.8	638	11.2	11
	HST off lease short term	84	84	84	84	7.5					
	HST off lease medium term	24	24	24	24	7.5					
	Class 37	53	53	-	-	-	-	-	-	-	-
	Class 57/0	12	12	0	0		0.2	0.2	0	-	
	Class 57/3 & /6	21	21	4	4				0		
	Class 59	15	15	-		-	0.7	0.7	-	-	-
	Class 60	100	100	-		-	1.0	1.0	-	-	-
	Class 66 UIC1	299	299	-		-	15.8	15.8	-	-	-
	Class 66 UIC2	60	60	-		-	3.2	3.2	-	-	-
	Class 66 EuroIIIa	31	31	0		-	1.6	1.6	-	-	-
	Class 67	30	30	5	5		0.1	0.1	5	0.1	
	Class 68	34	34	22	22	5	1.0	1.0	120	1.9	2
	Class 69	12	12	-		-	-	-	-	-	-
	Class 70	37	37	-		-	1.5	1.5	-	-	-
	Class 73/1	14	14	-							
	Class 73/9	2	2	0							
	Class 73/9	11	11	5	5				20	0.4	
	Totals	**2624**	**5524**	**1929**	**4829**		**95**	**95**	**5706**	**100**	**100**

[1] Limited introduction during 2018.

A review of the following tables will show that certain main engine and transmission types are used for multiple train classes; obtaining certain data for a particular engine or transmission can then often be used across multiple classes.

A substantial proportion of the fleet uses a comparatively small proportion of different types of equipment, which is useful when considering the potential development costs for any potential upgrades.

For hydraulic and mechanical transmission DMUs (Table 10) the engine supply in the last 15 years has been dominated by MTU. Prior to that Cummins was the main supplier with some engines supplied by Perkins. The spilt between Cummins and Perkins was due to British Rail having a dual supplier sourcing strategy. Although there are 11 engine models in total, they only come from six model families, often with only minor difference between different engine models.

The engine power has also steadily increased over time for similar DMUs to provide more traction power and better performance (e.g. acceleration and maximum speed) as well as being able to provide more power for greater auxiliary loads (e.g. air conditioning).

Table 10 GB fleet of DMUs with hydraulic and mechanical transmissions by class (or subclass as appropriate) with build year and engine manufacturer, model and maximum power

Class	Build year	Stock manufacturer (if still extant)	Engine manufacturer	Engine model	Emissions stage	SCR fitted?	Engine power (hp)	Engine power (kW)
142	1985-87		Cummins	LTA10 6H 10L	None	N	225	186
143	1985-86		Cummins	LTA10 6H 10L	None	N	225	186
144	1986-87		Cummins	LTA10 6H 10L	None	N	225	186
150	1984-87		Cummins	NT855R5	None	N	286	213
153	1988		Cummins	NT855R5	None	N	286	213
155	1988		Cummins	NT855R5	None	N	286	213
156	1987-89		Cummins	NT855R5	None	N	286	213
158	1989-92		Cummins	NTA855R1	None	N	350	260
158	1989-92		Cummins	NTA855R3	None	N	400	300
158	1989-92		Perkins	2006-TWH	None	N	350	260
159	1989-92		Cummins	NTA855R3	None	N	400	300
159	1989-92		Cummins	NTA855R1	None	N	350	260
165	1990-92		Perkins	2006-TWH	None	N	350	260
165	1990-92		Perkins	2006-TWH	None	N	350	260
166	1992-93		Perkins	2006-TWH	None	N	350	260
168	1998-2004	Bombardier	MTU	6R183TD13	UIC1/2	N	422	315
170	1998-2005	Bombardier	MTU	6R183TD13	UIC1/2	N	422	315
171	1999-2004	Bombardier	MTU	6R183TD13	UIC1/2	N	422	315
172	2010-12	Bombardier	MTU	6H1800R83	IIIA	N	483	360
172	2010-12	Bombardier	MTU	6H1800R83	IIIA	N	483	360
175	1999-2001	Alstom	Cummins	N14	None	N	450	336
180	2000-01	Alstom	Cummins	QSK19	None	N	750	560
185	2005-06	Siemens	Cummins	QSK19	None	N	750	560
195	2018-	CAF	MTU	6H1800R85L	IIIB	Y	523	390
196	2019-	CAF	MTU	6H1800R85L	V	Y	523	390
TfW CAF	2020-	CAF	MTU	6H1800R85L	V	Y	523	390

For electrical transmission DMUs (Table 11) the older engines were all supplied by Cummins. For the engines currently manufactured by MTU, Deutz and MAN there is far less variation in the number of available models (only one engine per DMU manufacturer is used).

Table 11 GB fleet of DMUs with electrical transmission by class (or subclass as appropriate) with build year and engine manufacturer, model and maximum power and build year

Class	Build year	Stock manufacturer (if still extant)	Engine manufacturer	Engine model	Emissions stage	SCR fitted?	Engine power (hp)	Engine power (kW)
220	2000-01	Bombardier	Cummins	QSK19	Road Euro II	N	750	560
221	2001-02	Bombardier	Cummins	QSK19	Road Euro II	N	750	560
222	2003-05	Bombardier	Cummins	QSK19	Road Euro II	N	750	560
230	1980	VivaRail	Ford	Duratorq3.2	IIIB	?	400	300
755/3	2019-	Stadler	Deutz	V8016L	IIIB	Y	640	480
755/4	2018-	Stadler	Deutz	V8016L	IIIB	Y	640	480
TfW Bimode 4	2019-	Stadler	Deutz	V8016L	IIIB	Y	640	480
TfW Trimode 4	2019-	Stadler	Deutz	V8016L	IIIB	Y	640	480
TfW Trimode 3	2019-	Stadler	Deutz	V8016L	IIIB	Y	640	480
769	1988-92		MAN	D2876	IIIB	Y	523	390
800/0	2015-	Hitachi	MTU	12V1600R80L	IIIB	Y	940	700
800/1	2015-	Hitachi	MTU	12V1600R80L	IIIB	Y	523	390
800/2	2015-	Hitachi	MTU	12V1600R80L	IIIB	Y	523	390
800/3	2015-	Hitachi	MTU	12V1600R80L	IIIB	Y	940	700
802/0	2018-	Hitachi	MTU	12V1600R80L	IIIB	Y	940	700
802/1	2018-	Hitachi	MTU	12V1600R80L	IIIB	Y	940	700
802/2	2018-	Hitachi	MTU	12V1600R80L	IIIB	Y	940	700
802/3	2018-	Hitachi	MTU	12V1600R80L	IIIB	Y	940	700
80x	2022	Hitachi	MTU	12V1600R80L	V	Y	940	700
810	2022	Hitachi	MTU	12V1600R80L	V	Y	940	700

In contrast to DMUs, for electrical transmission locomotives (Table 12) the engines supplied are much more varied due to the nature of the locomotive fleet. The newest design locomotives were produced in comparatively small numbers and have engines manufactured by GE/Jenbacher (Class 70) and CAT (Class 68); these engine designs should be capable of being modified to meet future emission standards for new build locomotives. The HST (Class 43) fleet, now mostly retired, was re-engined 10-15 years ago with mainly (88%) MTU (88%) engines and a smaller number of MAN engines. (The latter variants are being retired imminently).

The most significant locomotive or power car engine in terms of overall numbers is the EMD 710 engine which is used in the Class 66 and Class 67 (and soon in the Class 69 rebuilds). The older EMD 645 engine has been used in a number of new build (Cass 59) and re-engined (Class 57) locomotives; this engine shares significant design elements with the newer 710 engines. For the older locomotive types (which have comparatively small numbers and total mileage), virtually all the engine manufacturers, English Electric (and successors) and Mirrlees-Blackstone, have been taken over by MAN.

Table 12 GB locomotive engines (all electrical transmission) by class (or subclass as appropriate) with build year and engine manufacturer, model and maximum power

Class	Build year	Stock manufacturer (if still extant)	Engine manufacturer	Engine model	Emissions stage	SCR fitted?	Engine power (hp)	Engine power (kW)
HST ongoing	1975-82	Wabtec (Brush)	MTU	16V4000R41R	UIC2	N	2250	1678
HST off lease in short term	1975-82	Wabtec (Brush)	MTU	16V4000R41R	UIC2	N	2250	1678
HST off lease in short term	1975-82	Wabtec (Brush)	MAN	12VP185	UIC2	N	2250	1678
Class 37	1960-1965		English Electric	EE 12CSVT	None	N	1750	1305
Class 57/0		Wabtec (Brush)	EMD	12-645-E3	None	N	2500	1860
Class 57/3 & /6		Wabtec (Brush)	EMD	12-645-F3B	None	N	2750	2051
Class 59	1985-95	EMD	EMD	16-645-E3C	None	N	3300	2460
Class 60	1989-93	Wabtec (Brush)	MAN ES (ex M-B, Paxman)	MB275T-16	None	N	3100	2300
Class 66 UIC1	1998-2005	EMD	EMD	12N710G3B-EC	UIC1	N	3200	2386
Class 66 UIC2	2006-08	EMD	EMD	12N710G3B-EC	UIC2	N	3200	2386
Class 66 EuroIIIa	?2013-2015	EMD	EMD	12N710G3B-EC	IIIA	N	3200	2386
Class 67	2001-02	EMD	EMD	12N710G3B-EC	UIC1	N	3200	2386
Class 68	2013-16	Stadler	CAT	C175-16	IIIA	N	3800	2800
Class 69			EMD	12N710G3B-EC	IIIA	N	3200	2386
Class 70	2009-17	GE	GE/Jenbacher	Jenbacher 616	IIIA	N	3690	2750
Class 73/1	1965-67		English Electric	EE 4SRKT mkII	None	N	600	448
Class 73/9	1965-67		Cummins	QSK19	IIIA	N	750	560
Class 73/9	1965-67		MTU	8V4000R80L	IIIA	N	1600	1196

The overall GB rail diesel engine fleet (Table 13) is dominated by the DMU engines supplied by MTU and Cummins. A number of Cummins-engined Pacer family DMUs are being scrapped at the moment which will end the use of the LTA series engines and reduce Cummins’ market share. The locomotive and power car engine market is dominated by EMD engines with just over half the overall total of such engines, but a far larger share by locomotive mileage. The engine manufacturers that are now part of MAN have been grouped together.

Table 13 GB rail engine fleet

Engine manufacturer	Engine model	Number of units	Proportion of total units	
MTU	12V1600R80L	759	14%	38%
	16V4000R41R	169	3%	
	6H1800R83	93	2%	
	6H1800R85L	409	7%	
	6R183TD13	647	12%	
	8V4000R80L	11	0.2%	
Cummins	LTA10 6H 10L	284	5%	37%
	N14	70	1%	
	NT855R5	587	11%	
	NTA855R1	293	5%	
	NTA855R3	84	2%	
	QSK19	700	13%	
EMD	12N710G3B-EC	432	8%	9%
	12-645-F3B	21	0.4%	
	16-645-E3C	15	0.3%	
	12-645-E3	12	0.2%	
Perkins	2006-TWH	334	6%	6%
Deutz	V8016L	250	5%	5%
MAN	D2876	76	1%	5%
MAN-ES	12VP185	24	0.4%	
MAN-ES	MB275T-16	100	2%	
English Electric	EE 12CSVT	53	1%	
English Electric	EE 4SRKT mkII	14	0.3%	
GE/Jenbacher	Jenbacher 616	37	1%	1%
CAT	C175-16	34	1%	1%
Ford	Duratorq3.2	16	0.3%	0.3%
Totals		**5524**	**100%**	**100%**

As regards transmission types used in GB rolling stock (Table 14), DMUs traditionally have hydraulic transmission and locomotives have electric transmission. In the last 20 years high speed DMUs have started to use electric transmission (starting with the Voyagers), and in the last decade mechanical transmission has taken over from hydraulic transmissions for low speed local or regional DMUs.

Table 14 GB rail engine transmission types

Transmission type	Number of units	Proportion
Hydraulic - Torque converter + Fluid Coupling	2522	46%
Mechanical - Torque converter + 6 Speed Auto	502	9%
Electric	2500	45%
Totals	**5524**	**100%**

As regards models of hydraulic transmission types used in DMUs (Table 15), Voith have supplied all the hydraulic transmissions with the vast majority being 2-speed transmission (T211R family products) used in lower speed DMUs. All the mechanical transmissions have been supplied by ZF; the newer Ecolife model is an evolution of the older Ecomat model.

Table 15 GB rail hydraulic and mechanical transmission models

Transmission type	Transmission manufacturer	Transmission model	Number of units	Proportion
Hydraulic	Voith	T211R	2299	76%
Hydraulic	Voith	T312R	223	7%
Mechanical	ZF	Ecomat4	93	3%
Mechanical	ZF	Ecolife	409	14%
		Totals	**3024**	**100%**

As regards the model of final drives used in DMUs (Table 16), Gmeinder have supplied all the final drives used with the older Voith T211R 2 speed transmissions. ZF final drives have been used with all mechanical transmissions and the newer Voith T211R 2-speed transmissions. Voith final drives have been used with all the Voith 3-speed transmissions (T312R family of products).

Table 16 GB rail final drives (hydraulic and mechanical transmissions only)

Final drive manufacturer	Final drive model	Number of units	Proportion
Gmeinder	GM190	1093	36%
Gmeinder	GM180	559	18%
ZF	Family of similar models	1149	38%
Voith	SK485	223	7%
	Totals	**3024**	**100%**

9.3 Fleetwide emission standards

Engines in the GB diesel rail fleet were manufactured at different times and so subject to a wide range of emission regulatory regimes. Just under 40% (by 2018 diesel usage) were manufactured prior to any emission standards.

The rail industry was originally self-regulated with the Union International des Chemin-de-Fer (UIC) creating emission standards, which were mandatory in some countries and voluntary in others (e.g. the UK). Some engine manufacturers would voluntarily only sell UIC emission standards-compliant engines in all European countries even if not mandated, for example EMD and MTU in the UK. Hence a large number of GB locomotives and DMUs were covered before mandatory standards across Europe were implemented. Within the next few years more than a third of the fleet will have engines complying with the compulsory emission standards of Euro IIIA, IIIB or V.

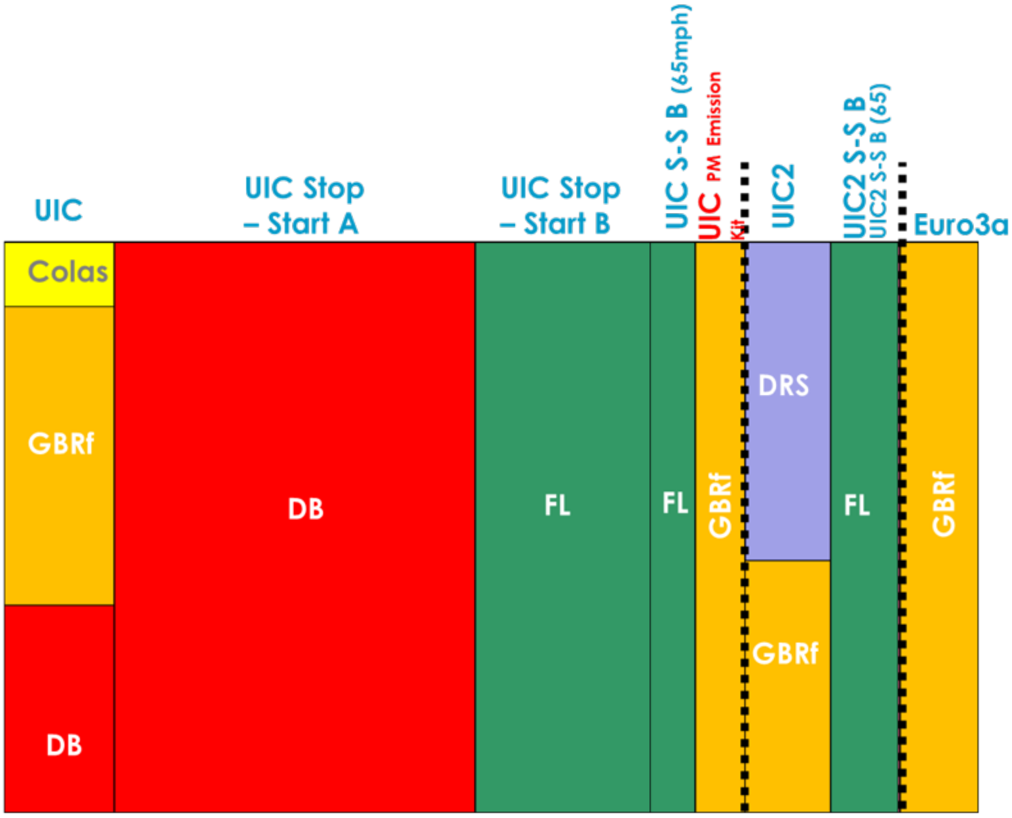
Table 17 GB rail engines by emission standard

Emission standard	Number of units	Proportion
None	2090	38%
UIC-1	329	6%
UIC-1/2	647	12%
UIC-2	253	5%
Road Euro II	475	9%
Rail Euro IIIA	220	4%
Rail Euro IIIB	953	17%
Rail Euro V	557	10%
Totals	**5524**	**100%**

9.3.1 Class 66 emission variants

Class 66s represent over 85% of diesel freight mileage and fuel consumption in recent years, so an understanding of the history of this class is important. The Class 66 fleet was built with engines to three emissions standards over 17 years, ordered as 27 separate orders and some have had up to four owners/lessees. They also have two final gear ratios: a reduced gear ratio was later fitted to some locomotives to enable better performance with heavier loads at the expense of reducing the maximum speed from 75 mph to 65 mph. Automatic engine stop/start (AESS) systems from two manufacturers were fitted to some locomotives and some have also received emissions upgrades (focused on PM reduction). Overall, this has resulted in a fleet with nine different equipment permutations for emissions purposes (see Figure 56) with three different engine types to comply with three emission standards in force at the various times they were in production. All other freight locomotives were built (or had replacement engines fitted) over a typical 3-4-year window, with engines all to a common specification hence these do not need to be considered in the same level of detail.

Figure 56 Class 66 fleet breakdown (as of October 2019) showing the nine different specification permutation relevant to emissions on an operator basis



Within the project the three engine variants were considered along with locomotives with and without stop start, and locomotives with both 75 mph and 65 mph maximum speed gearing, without having to cover all nine permutations individually. Thus, this methodology obviates the need for specific testing for every possible variant and essentially leverages resources spent on any testing.

9.4 Compiled data

Most of the required engine and all transmission and final drive data for DHMUs and DMMUs were obtained for each train or locomotive class. The data was obtained from a combination of TOCs, FOCs and ROSCOs, as well as direct from manufacturers and suppliers. Some engine certification testing data was also obtained from regulatory bodies in countries where filing such data is mandatory (e.g. the US). Situations where proxy data had to be used are discussed in Section 9.5.

Table 18 summarises the availability and quality of emission testing data used for this project while Table 19 and Table 20 summarise the DMU and locomotive OTMR data, respectively, that were compiled for this project.

Table 18 Availability and quality of rail engine testing data compiled for this project

Engine manufacturer	**Engine model**	**High quality emsission testing**	**C1 regulatory test cycle points**	**F regulatory test cycle points**	**Other test data**	**Other test cycle data**	**Compliance letter**
MTU	12V1600R80L		Y				
	16V4000R41R	Y		Y		Y	
	6H1800R83						Y
	6H1800R85L						Y
	6R183TD13	Y		Y			
	8V4000R80L	Y	Y				
Cummins	LTA10 6H 10L			Y	Y	Y	
	N14				Y	Y	
	NT855R5	Y		Y	Y	Y	
	NTA855R1	Y		Y	Y	Y	
	NTA855R3	Y		Y	Y	Y	
	QSK19			Y	Y	Y	Y
EMD	12N710G3B-EC	Y				Y	
	12-645-F3B	Y				Y	
	16-645-E3C	Y				Y	
	12-645-E3	Y				Y	
Perkins	2006-TWH			Y	Y	Y	
Deutz	V8016L						Y
MAN	D2876						
MAN-ES	12VP185						
MAN-ES	MB275T-16						
English Electric	EE 12CSVT	Y					
English Electric	EE 4SRKT MkII	Y					
GE/Jenbacher	Jenbacher 616				Y	Y	Y
CAT	C175-16	Y			Y	Y	
Ford	Duratorq3.2						

Table 19 DMU OTMR data compiled for this project

Type	Class	OTMR download	Other - e.g. drive cycle from engine computer	Drive cycle proxy
Diesel hydraulic/ mechanical multiple unit	142			
	143			
	144			
	150			As 156
	153	Y		
	155			As 156
	156	Y		
	158	Y		
	158	Y		
	158	Y		
	159	Y		
	159	Y		
	165	Y		
	165	Y		
	166	Y		
	168	Y		
	170	Y		
	171			As 168/170
	172	Y		
	172	Y		
	175			
	180	Y		
	185	Y	Y	
	195			As 170
	196	Not in service yet		
	TfW CAF	Not in service yet		
Diesel electrical multiple unit	220	Y		
	221	Y		
	222			As 220
	230			
	755/3			
	755/4			
	TfW Bimode 4	Not in service yet		
	TfW Trimode 4	Not in service yet		
	TfW Trimode 3	Not in service yet		
	769	Not in service yet		
	800/0		GPS + audio data	
	800/1		GPS + audio data	
	800/2		GPS + audio data	
	800/3		GPS + audio data	
	802/0		GPS + audio data	
	802/1		GPS + audio data	
	802/2			Other 802
	802/3			Other 802

Table 20 Locomotive and power car OTMR data compiled for this project

Type	Class	OTMR download	Other - e.g. drive cycle from engine computer	Drive cycle proxy
Locomotives / Power cars - electric transmission	HST ongoing	Y	Y	
	HST off lease short term			Y
	HST off lease medium term			Y
	Class 37	Y		
	Class 57/0			Y
	Class 57/3 & /6			Y
	Class 59	Y		
	Class 60			Y
	Class 66 UIC1	Y		
	Class 66 UIC2	Y		
	Class 66 EuroIIIa			Y
	Class 67			Y
	Class 68	Y		
	Class 69			Y
	Class 70	Y		
	Class 73/1	Y		
	Class 73/9	Y		
	Class 73/9	Y		

9.5 Proxies used for data gaps

Some or all of the data required for certain locomotives or trains could not be obtained from key data holders in the GB rail industry. Outstanding data and the solutions used to derive proxy emission factors by notch are listed below.

9.5.1 Class 57

Data still required: OTMR.

Proxy: Use Class 66 drive cycle with light loads.

9.5.2 Class 60

Data still required: OTMR.

Proxy: Use Class 66 drive cycle with heavy loads.

9.5.3 Class 68

Data still required: Additional engine control and auxiliary loads from Stadler, emissions data from CAT.

Proxy: Detailed US emission testing data for the C175-16 engine with adjustment for known set-up differences for the engine as fitted to Class 68 in GB including auxiliary loads.

9.5.4 Class 175

The Class 175 fleet is small in overall terms and is used on longer distance services mainly in Wales by Transport for Wales (TfW). It represents around 1% of the passenger diesel fleet by both fuel usage and mileage.

Data still required: OTMR and engine control set up from TfW.

Proxy: Turbostar OTMR for power usage and some non-rail Cummins N14 emission testing data.

9.5.5 Class 195/196

Data still required: OTMR data from Northern and emissions data from MTU/Daimler (engine design IP resides with Daimler).

Proxy: Class 172 OTMR and emission testing from an older, less powerful 6H 1800 R83-engine in the same engine family.

9.5.6 Class 755

This is the first lower speed regional electric transmission bi-mode DMU and is set up very differently to other electrical transmissions multiple units with the aim being to use engines nearer the top of their power ranges for better efficiency and emissions and to operate with fewer engines when less power is required.

Data still required: OTMR data from Greater Anglia, engine control data from Stadler, emissions data from Deutz.

Proxy: Voyager.

10 Discussion

In this section the importance of idle in drive cycles for all major train categories is reviewed. Three specific examples of how emission factors per unit energy (in g/kWh) by notch can be applied are then provided.

10.1 Emissions in idle are a key air quality issue for rail

A clear finding is that for all locomotive and train classes emissions of air pollutants (specifically NO_X and PM) do not directly correlate with power output and thus with fuel consumption (and so CO_2 emissions). The fundamental reason for this is that combustion is most efficient in the highest engine notches, i.e. where there is the least production of other pollutants occurring.

A more detailed inspection of emission factors by notch shows that NO_X is significantly higher in idle versus other notches for all engine types. A similar but less pronounced trend is present for PM where idle is always higher versus other notches but to a lesser degree than for NO_X. For PM in non-idle notches there is also a clear and steeper declining trend for emission factor values between the lower and higher notches than for NO_X (compare Figure 37 and Figure 38 , NO_x and PM emissions by notch for the Class 158/159 Cummins 400 hp engine), often with less than 15% variation in NO_X between the high notches. Although not considered here, the variation between (non-idle) notches for other AQPs such as hydrocarbons tends to lie between that for PM and NO_X, with NO_X being the flattest between notches and PM the steepest. This lack of variation has meant emissions have been harder to measure and likely contributes to previous assumptions that NO_X emissions could be treated as proportional to engine power.

10.1.1 High proportion spent in idle for all GB drive cycles

A large body of OTMR data was collected as part of this project, which included data not just for specific services but also for multi-week for some units and in some cases multi-month for whole fleets for certain classes. This resource permitted derivation of robust actual drive cycles for many classes. Considering five example categories:

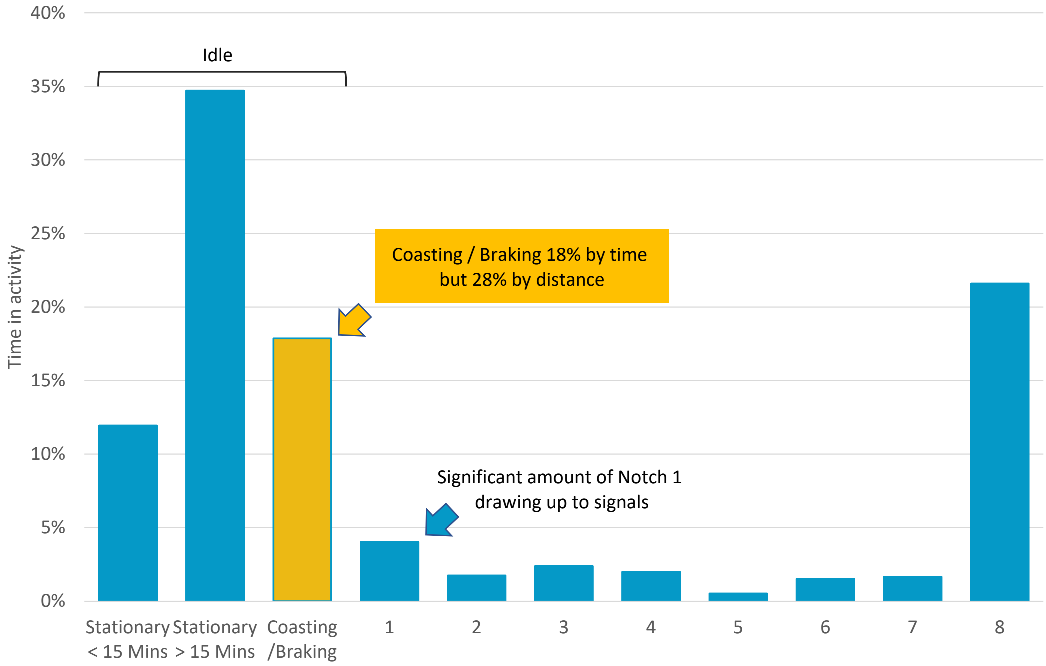
- **HST** – diesel electric transmission (see Figure 25 , Figure 26 and Figure 27): a short form HST (2 power cars + 4 coaches) spends 60% of time in idle while a 2 power cars + 8 coaches set on a high stopping diagram spends 50% of time in idle.
- **Class 158** – diesel hydraulic transmission (see Figure 41): A weekly drive cycle (including all time spent at depots and on layovers between services) shows over 70% of engine running time is spent in idle. High level analysis of data from a TOC’s complete Class 158 fleet showed around 75% of engine running time is spent in idle.
- **Class 170** – diesel hydraulic transmission: High level analysis of data from a TOC’s complete Class 170 fleet showed around 73% of engine running time is spent in idle.

- **Voyager** – diesel electric 'continuously variable' transmission (see Figure 33): Over 60% of in-passenger service cycle time is spent in the Traction Prepared mode.
- **Class 66** – diesel electric transmission (see Figure 18): For all operators, around 70% of time is spent in idle.

Thus a key finding is the high amount of engine operating time (always over 50%, and usually over 60% in most cases) that is spent in idle for all types of passenger trains and freight locomotives.

Given then that emissions in idle are proportionately higher than in other notches it is important to consider the amount of time spent in idle during a typical drive cycle and whether useful work is being done (the train is coasting versus stationary). Figure 57 shows an example container train run from Felixstowe to Birmingham (which includes shunting time at the end of the journey) where over 18% of the time is spent coasting and braking while covering over 28% of the total mileage. It is important therefore to account for productive time (coasting) in idle when deriving emission factors based on a real-world drive cycle; this can also be seen in Figure 26 for HSTs where a larger proportion of time (24%) is spent coasting.

Figure 57 Time spent in each notch for a Class 66-hauled container train trip between Felixstowe and Birmingham



However, while coasting is a substantial part of the time spent in idle, it is important to note that in all real-world drive cycles for any locomotive or train class the most time is spent in idle. For many passenger trains much of this time (often a minimum of 30% of total engine running time) includes 'warming up' in the morning to build enough air brake pressure, time waiting at termini between journeys, and time for cleaning in the off-peak on some days. Solutions to reduce the amount of time in idle, such as alternative means to maintain air brake pressure, can be expected to have a significant impact on rail emissions of air pollutants.

10.2 Improved NAEI factors

The main calculation of rail emissions for the NAEI uses emission factors in units of g/train-km or g/vehicle-km times national fleet-wide vehicle-km activity data (in units of train or vehicle-km). Emissions by notch combined with an understanding of the typical drive cycle for each locomotive or train class can be used to derive improved emission factors in units of g/km. OTMR data is needed to fully understand the drive cycle to correlate the engine operation and emissions produced with distance travelled. It is particularly important to understand when the engine is at idle but distance is being covered, i.e. the train is coasting, since this impacts an average emission factor in units of g/km.

Although most long-formed HSTs have now been withdrawn from mainline service, a good understanding of their emissions is needed because of their prominence in the NAEI timeseries of rail emissions since 1976. It is especially important to fully account for the impact of the HST re-engining that took place between 2007 and 2009 so that the rail industry can demonstrate the significant reductions to emissions which have already taken place. Furthermore, short-formed HSTs will be in service for a further decade, although they will have a different emissions profile because of a lower maximum speed and lower loadings.

10.2.1 HST case study

Here an example for the long formation HST shows how the new emission factors by notch can be used to revise the NAEI emission factors. The key additional information to relate emission factors by notch (in g/kWh) is representative OTMR data. This relates the engine operation (time spent in different notches) to distances covered during a typical drive cycle which would include warm up time, travel to and from the depot, time spent in stations (including the terminus end power car being shut down), and actual revenue service. Once total emissions are derived for a typical daily diagram (by multiplying the time spent in each notch by the relevant emission factor for each notch) these can be divided by the distance of that diagram to drive an NAEI emission factor in units of g/train-km.

Revised factors (drive cycle weighted) are 14.4 g/vehicle-km for NO_X and 0.17 g/vehicle-km for PM. The new NO_X emission factor for the MTU engine is 80% of the emission factor for the previous Paxman Valenta while the MTU PM emission factor is 7% of that for the Valenta engine. These values are in line with expectations on prevailing emission standards (essentially Euro IIIA; see Section 2) for the MTU engine.

Revising these emission factors in the NAEI will have a significant impact. For instance, the annual NO_X emissions for 2016 would be lower by 1,755 tonnes (a 7% reduction in total NO_X emissions from rail). The impact is particularly marked for PM since in recent years HSTs have accounted for 49% of total PM emissions from rail. The annual PM emissions for 2016 with the revised HST PM emission factor would be lower by 301 tonnes (a 32% reduction in total PM emissions from rail). It is noteworthy that the current HST PM factor was suspected to be unusually high at the time of the switch to a per passenger vehicle-km basis in the NAEI. Furthermore, the 2014 Kings College London study[86] was unable to clearly detect rail emissions at sites adjacent to the GWML near Ealing and the ECML near Finsbury Park above road-dominated background levels. These locations had high HST traffic levels at the time and the authors expected to detect their emissions based on the NAEI HST emission factors. However, those factors did not account for HST re-engining and that the PM emission factor they used too high as this work shows.

10.2.2 Improvements made for the 2018 NAEI

Based on work carried out for the earlier RSSB project[87] that acted as a prelude to this project, updated g/km emission factors were developed based on g/kWh emission factors and available OTMR data for a number of train and locomotive classes. The tables below of the revised factors can be compared to Table 3 , Table 4 and Table 5 in Section 4.

Intercity passenger train emission factors are shown in Table 21 . The main changes due to the re-engining of the HST fleet were discussed previously in Section 10.2.1. The HST fleet operates with a varying (but fixed) number of passenger coaches and the drive cycle data now available allows this variation to be taken into account when deriving emission factors in g/km. For the newly introduced Hitachi bi-mode IET (fitted with Rail Euro Stage IIIB compliant engines) emission factors were not then available so the longest length revised HST factor was used as conservative interim default. For intercity trains, as well as NO_x and PM, testing data was available for CO and HC, so factors for NMVOC, CH_4, benzene and 1,2-butadiene (which are based on proportions of HC emissions) were also revised.

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[86] Fuller, G., T. Baker, A. Tremper, D. Green, A. Font, M. Priestman, D. Carslaw, D. Dajnak, and S. Beevers (2014). *Air pollution emissions from diesel trains in London*. Environmental Research Group, King's College London.

[87] Grennan-Heaven, N. and M. Gibbs (2019). *2769 - AQ0001a: Improving Diesel Rail Emission Factors - Initial Study*. RSSB.

Table 21 NAEI intercity passenger train emission factors (g/vehicle-km; revised factors highlighted in green)

	Previous	**Revised**				
Train class	**43**	**43+5 (MTU)**	**43+7 (MTU)**	**43+8 (MTU)**	**43+9 (MTU)**	**IET**
CO	4.8	1.2	1.4	1.3	1.2	1.2
NOx	17.9	6	16.5	18.1	16	16
HC	2.1	0.4	0.4	0.4	0.3	0.3
NMVOC	2	0.4	0.4	0.3	0.3	0.3
CH_4	0.1	0	0	0	0	0
Benzene	0	0	0	0	0	0
1,3-butadiene	0	0	0	0	0	0
PM_{10}	2.4	0.2	0.2	0.2	0.2	0.2

For regional trains (see Table 22), changes were made to the NAEI emission factors for Class 150-172 (inclusive) DMUs and the Class 68 locomotive. As discussed in Section 7, DMU drive cycles involve a substantial amount of time in idle (a minimum of 75%) since, unlike road vehicles, most DMU transmissions allow the engine to be in 'idle' while coasting and braking. While the emissions in idle are comparatively higher on a g/kwh basis, the lower power and longer time in idle leads to a reduction in both the NO_x and PM emission factors. The previous NAEI 'new Stage IIIB locomotive hauled' factors were used for the Class 68 locomotive-hauled passenger services.

Table 22 NAEI regional passenger train emission factors (g/vehicle-km; revised factors highlighted in green)

Train class	**150**	**153**	**155**	**156**	**158**	**159**
Train type	**Sprinter**					**Turbo**
Data Proxy	156	156	156	156	158	158
CO	1.6	1.6	1.4	1.5	2.1	2.2
NOx	5.2	5.2	5.2	5.2	3.9	3.9
HC	0.3	0.3	0.2	0.2	1.1	1.1
NMVOC	0.3	0.3	0.2	0.2	1	1.1
CH4	0	0	0	0	0	0
Benzene	0	0	0	0	0	0
1,3-butadiene	0	0	0	0	0	0
PM_{10}	0.08	0.08	0.08	0.08	0.52	0.52

Table 22 (continued) NAEI regional passenger train emission factors (g/vehicle-km; revised factors highlighted in green)

Train class	**165**	**166**	**168**	**170**	**171**	**172**	**68**
Train type	**Turbo**		**Turbostar**				**N/A**
Data Proxy	165	165	170	170	170	172	N/A
CO	7.9	7.8	5	5.5	6.2	6.2	6.6
NOx	1.4	1.4	3.9	3.9	3.9	4.1	3.7
HC	1	1	0.2	0.2	0.2	0.2	0.4
NMVOC	0.9	0.9	0.2	0.2	0.2	0.2	0.3
CH4	0	0	0	0	0	0	0
Benzene	0	0	0	0	0	0	0
1,3-butadiene	0	0	0	0	0	0	0
PM_{10}	0.16	0.16	0.06	0.06	0.06	0.09	0.05

Revised freight emission factors are shown in Table 23 . The Class 66 fleet contains three different engine emission control variants (UIC1, UIC2 and Euro IIIA) but was previously treated in the NAEI as all being UIC1 (the lowest emission standard). For the 2017 NAEI the previous Class 66 NAEI NO_x factor of 387.5 g/km which was seen to be impossibly high was replaced with a lower conservative value from an SRA study[88]. New factors based on real drive cycles from OTMR and the new notch-based factors in g/kwh were combined to produce g/km factors for all three emission control variants. The new UIC1 NO_x factor is 8% lower than the conservative replacement value used for the 2017 NAEI, while NO_x factors for the UIC2 and Euro IIIA variants are considerably lower. Factors for Classes 68 and 70 were added using the Class 66 Euro IIIA factors as a conservative proxy. As well as for NO_x and PM, data was available for CO and HC, so factors for NMVOC, CH_4, benzene and 1,3-butadiene (which are based on proportions of HC emissions) were also revised for freight locomotives.

Table 23 NAEI freight emission factors (g/km; revised factors highlighted in green)

	Previous		**Revised**				
Train class	**Class 66**	**New freight trains**	**Class 66 UIC1**	**Class 66 UIC2**	**Class 66 Euro IIIA**	**Class 68**	**Class 70**
Fuel (kg/km)	4.8	4.8	4.7	4.7	4.7	4.7	4.7
CO	43.2	74.9	12.01	39.96	3.8	3.8	3.8
NOx	120	81.3	111.4	61.6	36.1	36.1	36.1
HC	22.4	4.3	1.68	4.55	1.13	1.13	1.13
NMVOC	21.6	4.1	1.6	4.4	1.1	1.1	1.1
CH4	0.8	0.2	0.1	0.2	0	0	0
Benzene	0.4	0.08	0	0.1	0	0	0
1,3-butadiene	0.2	0.04	0	0	0	0	0
PM_{10}	5.1	0.5	2.7	2.1	1.1	1.1	1.1

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[88] Hobson, M. and A. Smith (2001). *Rail and road emissions model*. Strategic Rail Authority.

The overall effect of making these changes to the NAEI emission factors for rail is significant for many pollutants. For instance, total NO_x emissions from rail declined by around 10,000 tonnes when the revised Class 66 factor was used for the 2017 NAEI and by a further 8,000 tonnes when revised DMU NO_x factors were used for the 2018 NAEI. The cumulative impact is that estimated NO_x rail emissions fall from around 4% (in the 2016 NAEI) to just under 2% of total UK NO_x emissions from all anthropogenic sources (in the 2018 NAEI). Similar changes apply to most years in the time series back to the mid-1980s when many Sprinter DMUs were introduced. Interestingly, these changes mean the UK NO_x emissions no longer exceed the 2010 National Emissions Ceiling Directive (NECD) ceiling for 2012[89].

10.2.3 Future potential improvements

Further improvements could be made to the 2019 NAEI, which will be compiled in late 2020 and published in Spring 2021. Revised NAEI emission factors in units of g/train-km or vehicle-km could be developed based on the new information collected for this project for Voyagers and Meridians (Classes 220, 221, 222) and IETs (Classes 800 and 802). Collection of OTMR data will be needed to enable g/km emission factors to be developed for other locomotives and trains such as Classes 57, 60, 175 and 195/196.

10.3 Evaluating emission scenarios

When combined with detailed OTMR data for specific routes, emission factors by notch can be used to demonstrate the sensitivity of emissions of NO_x, PM and CO_2 to various operational factors for both passenger and freight trains. A separate report for this project[90] explores various scenarios including the impacts of accelerating, coasting and braking on the emissions costs of:

- stopping (e.g. varying service patterns, signal delays)
- route features and infrastructure restrictions (e.g. reduced speeds at junctions)
- variations in loading (e.g. number of units, cargo lifted).

That report will help prioritise strategies to reduce rail emissions and will help inform and support investment cases for infrastructure improvements such as increasing gauge clearances, increasing freight loop entry and exit speeds, extending loop lengths to accommodate 775-m length trains, and signal improvements (e.g. three-aspect banner repeaters).

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[89] Richmond, B., A. Misra, M. Broomfield, P. Brown, E. Karagianni, T. Murrells, Y. Pang, N. Passant, B. Pearson, R. Stewart, G. Thistlethwaite, D. Wakeling, C. Walker, J. Wiltshire, M. Hobson, M. Gibbs, T. Misselbrook, U. Dragosits and S. Tomlinson (2020) *UK Informative Inventory Report (1990 to 2018)*. Ricardo Energy & Environment.

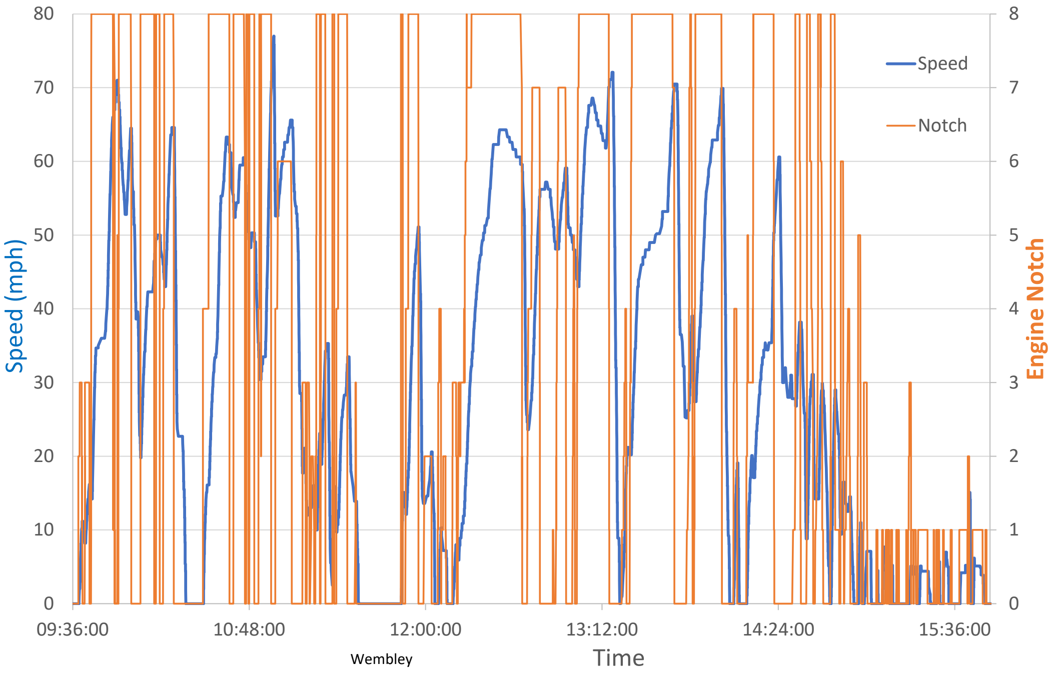
[90] Mansell, G., R. Brook, N. Grennan-Heaven and M. Gibbs (2020). *T1187 CLEAR: Fleet wide assessment of rail emissions factors – Emission scenarios report*. RSSB.

A particular example application, improved intermodal comparisons, is discussed below, showing how g/kWh factors can be used to derive a more accurate g/tonne-km factors for specific trips and loadings.

10.3.1 Improved intermodal comparisons

Analysis of an example Class 66-hauled container train between Felixstowe and Birmingham (Figure 58) was carried out by integrating NO_X emissions for time in each notch over the journey (including time shunting in the yards). Using this methodology total NO_X emissions (18.21 kg) are half of those using the recently revised Class 66 NAEI emission factor of 120 g/km (36.67 kg) as a result of accurately integrating the time in notch and being able to take account of coasting, this is in line with the analysis in the 2005 Technical University of Denmark work that analysed the advantages of a more detailed approach and not using single aggregate factors (also see the discussion of the effects of drive cycle in Section 2).

Figure 58 Engine notch and speed for a Class 66-hauled container train trip between Felixstowe and Birmingham



When incorporating TRUST consist (trainload) data the NO_X emission factor for this journey is 0.121 g/tonne-km versus the DfT average figure of 0.31 g/tonne-km[91]. This result has significant implications for performing more meaningful intermodal comparisons and shows the importance of using detailed emissions and loadings data. It will be important therefore to understand how variations in routes and loadings can then affect such emission factors. This issue is explored further in the associated report for this project on emission scenarios[92].

10.4 Improving understanding of rail's impact on local air quality

The current NAEI approach to estimating emissions uses typical traffic patterns (the activity) times simple average g/km emission factors for a locomotive or train class. No account is taken of different loadings or train stopping patterns. Therefore, currently the NAEI rail emission maps show the same amount of emissions per train type along the whole length of the railway line, when in reality there will be areas with higher emissions such as at stations and in sidings. A separate RSSB CLEAR project, T1186 Rail emissions and air quality mapping, is currently underway to address these issues and will utilise the emission factors developed by this project.

The more granular and comprehensive approach being followed in T1186 will combine detailed service data (train class, loadings, stopping pattern) initially NAEI-type g/km

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[91] DfT (2017). *Freight carbon review 2017*.

[92] Mansell, G., R. Brook, N. Grennan-Heaven and M. Gibbs (2020). *T1187 CLEAR: Fleet wide assessment of rail emissions factors – Emission scenarios report*. RSSB.

factors, and then later with 'average' OTMR data that incorporates normal variance in services (due to train load, signalling delays, etc.) and emission factors by notch. As such a detailed and more accurate spatial distribution of emissions could be built up which accounts for the mix of traffic types on different mainlines and locations and their speed profiles. For instance, the emissions profile of the Class 185 on TransPennine services (frequent stops, routes with heavy gradients and high-speed sections) will be very different to a Class 159 express service between Salisbury and London. This approach would allow identification of the most important national hot spots where there is the highest potential impact of local urban air quality and where improved infrastructure to minimize delays and increase route capacity could have the highest impact on emissions.

Such detailed spatial analyses combined with dispersion modelling could be conducted to assess the impact on ambient local air quality in and around stations, traction depots and freight yards in urban areas. Emission factors by notch for different classes and subclasses and a detailed understanding of time spent in idle in such locations could be used to evaluate how local concentrations of air pollutants might change in response to various mitigation measures such as emission controls or engine shut-down policies. This approach of using detailed activity data combined with emission factors for different engine modes is now being followed on a widespread basis for road vehicles and more recently for shipping[93], but until now has not been appropriate for the rail sector due to the lack of granularity in the emissions estimates.

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[93] Scarbrough, T., I. Tsagatakis, K. Smith, D. Wakeling, T. Smith, E. O'Keeffe and E. Hauerhoff (2017). *A Review of the NAEI Shipping Emissions Methodology*. Ricardo Energy & Environment.

11 Assessment of non-combustion emissions from rail

11.1 Introduction

Most transport emission studies have concentrated on emissions from internal combustion engines rather than abrasion. Road emissions represent the biggest transport emission source overall and with the introduction of greater numbers of electric vehicles there has started to be a more detailed consideration of abrasion particulate sources.

Vehicle particulate emissions still occur in electric vehicle-only areas, the so called 'Oslo Effect'[94], resulting from braking and rubber tyre wear. The UK NAEI currently estimates that road transport brake, tyre and road wear particulates are now higher than road transport combustion particulates[95]. Current UK NAEI rail emission estimates are based on combustion emissions only with no abrasion estimates. However, rail non-combustion emissions are significantly lower than for combustion emissions and a very small component of national particulate totals but are still of potential local/occupational health interest.

Rail transportation has higher efficiency, lower rolling resistance and lower material wear rates than road transport, resulting in a comparatively lower material volume produced as particulates[96]. But there is a lack of high-quality rail abrasion particle studies, with many being of narrow focus or having significant technical limitations. As such, non-combustion rail emissions data are focused in published research studies rather than in aggregated inventories. Many review papers of rail emissions focus on particular areas, for example focusing just on rail/wheel wear and braking but ignoring electrical contact/conductor wear, and do not attempt to quantify what total rail non-combustion emissions might be[97, 98, 99].

Abrasion particulates have been extensively studied in tunnel environments, allowing some background particulate levels to be eliminated that would make open-air studies more complex[100, 101]. These studies offer the current best understanding of the

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[94] Madsen, C., P. Rosland, D.A. Hoff, W. Nystad, P. Nafstad and O.E. Naess (2012). ‘The short-term effect of 24-h average and peak air pollution on mortality in Oslo, Norway’, *European Journal of Epidemiology* 27(9): 717-27.

[95] https://naei.beis.gov.uk/data/

[96] Lewis, R., and U. Olofsson (2004) ‘Mapping rail wear regimes and transitions’, *Wear* 257(7-8): 721-729.

[97] Abbasi, S., A. Jansson, U. Sellgren and U. Olofsson (2013). ‘Particle emissions from rail traffic: A literature review’, *Critical Reviews in Environmental Science and Technology* 43(23): 2511-2544.

[98] Fuller, G., T. Baker, A. Tremper, D. Green, A. Font, M. Priestman, D. Carslaw, D. Dajnak, and S. Beevers (2014). *Air pollution emissions from diesel trains in London*. Environmental Research Group, King’s College London.

[99] Gehrig, R., M. Hill, P. Lienemann, C.N. Zwicky, N. Bukowiecki, E. Weingartner and B. Buchmann (2007). ‘Contribution of railway traffic to local PM_{10} concentrations in Switzerland’, *Atmospheric Environment* 41(5): 923-933.

[100] Seaton, A., J. Cherrie, M. Dennekamp, K. Donaldson, J.F. Hurley and C.L. Tran (2005). ‘The London Underground: Dust and hazards to health’, *Occupational & Environmental Medicine* 62(6): 355-362.

[101] Martins, V., T. Moreno, L. Mendes, K. Eleftheriadis, E. Diapouli, C. A. Alves, M. Duarte, E. de Miguel, M. Capdevila, X. Querol and M.C. Minguillón (2016). ‘Factors controlling air quality in different European subway systems’, *Environmental Research* 146: 35-46.

particulate origins. However, it should be noted that in non-enclosed environments, for example on platforms, the particulate concentrations are less than 5% of those in tunnels[102]. This is due to dispersal rather than accumulation of the particulates[103], so the in-tunnel study conclusions on absolute levels of PM and the implications for health are not directly transferable. Nevertheless, abrasion particulate concentrations in open air are only likely to be significant to persons in very close proximity.

11.2 Characteristics of rail non-combustion emissions

Rail particulate emissions of abrasion origin make up a much smaller fraction of rail emissions compared to the abrasion-related emissions from road transport. Combustion emissions are both gaseous and particulates. Non-combustion emissions are almost all abrasion generated. There are very limited gaseous emissions such as ozone which is produced both directly from coronal discharge (when electrical discharge ionizes the surrounding air) and indirectly photochemically by UV from arcing between moving electrical contacts[104, 105].

Non-combustion related particulates are typically one to two orders of magnitude smaller than combustion particulates[106]. Measurement techniques and metrics used for combustion particulates are less appropriate for abrasion particles. Particle size categories typically monitored are PM_{10} or $PM_{2.5}$, i.e. a focus on combustion particulates. However, the mean size of rail origin abrasion particles is around 0.07 µm[107]. However, many studies have only looked at the larger PM_{10} and $PM_{2.5}$ in analysis and not included the smallest common measurement category of $PM_{0.1}$ with around 85% of rail origin abrasion particulates being smaller than 0.1 µm[108, 109].

Figure 59 presents the typical size distributions of abrasion PM from different sources.

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[102] Smith, J.D., B.M. Barratt, G.W. Fuller, F.J. Kelly, M. Loxham, E. Nicolosi, M. Priestman, A.H. Tremper, D.C. Green (2020). '$PM_{2.5}$ on the London Underground', *Environment International* 134: 105188.

[103] Gehrig, R., M. Hill, P. Lienemann, C.N. Zwicky, N. Bukowiecki, E. Weingartner and B. Buchmann (2007). 'Contribution of railway traffic to local PM_{10} concentrations in Switzerland', *Atmospheric Environment* 41(5): 923-933.

[104] Smith, L.I., F.L. Greenwood and O. Hudrlik (1946). 'Ozone (a laboratory ozonizer)', *Organic Syntheses* 26: 63-76.

[105] Dohan, J.M., and W.J. Masschelein (1987). 'The photochemical generation of ozone: Present state-of-the-art', *Ozone: Science & Engineering* 9(4): 315-334.

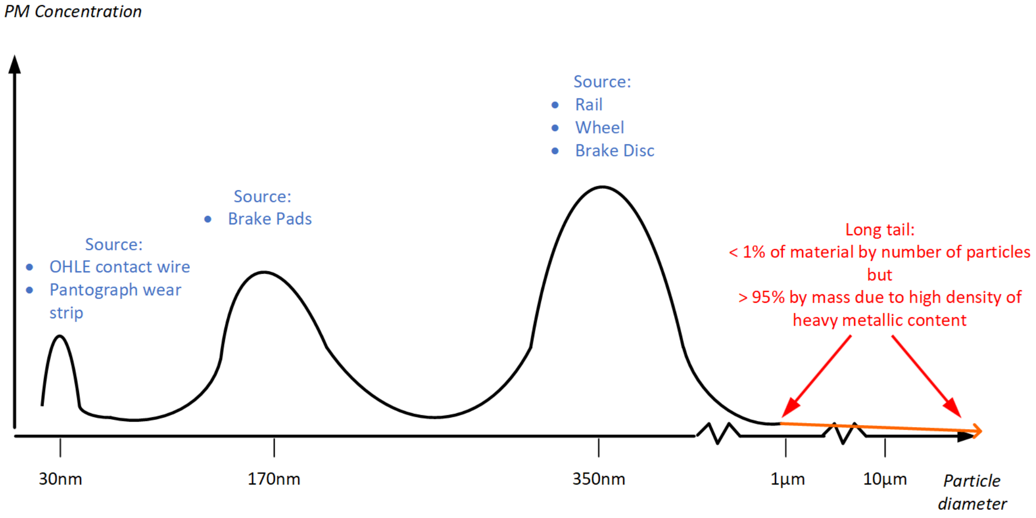
[106] Loxham, M., M.J. Cooper, M.E. Gerlofs-Nijland, F.R. Cassee, D.E. Davies, M.R. Palmer and D.A.H. Teagle (2013). 'Physicochemical characterization of airborne particulate matter at a mainline underground railway station', *Environmental Science & Technology* 47(8): 3614-3622.

[107] Ibid.

[108] Ibid.

[109] Smith, J.D., B.M. Barratt, G.W. Fuller, F.J. Kelly, M. Loxham, E. Nicolosi, M. Priestman, A.H. Tremper, D.C. Green (2020). '$PM_{2.5}$ on the London Underground', *Environment International* 134: 105188.

Figure 59 Abrasion PM size distribution



11.3 Main sources of rail abrasion particles

The main sources of rail abrasion particles, their chemistry and their varying proportion of total rail abrasion PM emissions are shown in Table 24 . There is significantly less carbon content (elemental or organic) compared with road transport abrasion as there is no rubber tyre or tarmac wear.

There are two main non-combustion rail particulate sources responsible for at least three quarters of emissions:

- From friction braking, although there are large variations in the quantity of particulates produced depending on the braking technology. For instance, some trains are fitted with regenerative or rheostatic braking that use electric traction motors to brake the train down to almost walking pace (by transferring energy into either the overhead line equipment/third rail or large resistor banks in newer diesel-electric rolling stock). This has a large reduction on the quantity of particulates produced[110], [111]. Disaggregating understanding of different material sources is often difficult in the rail environment, but recent studies have looked at collecting braking PM[112].
- Rail/wheel wear which is affected by many factors including train speed, track geometry/curvature, train suspension, and train mass[113].

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[110] Khodaparastan, M., A.A. Mohamed and W. Brandauer (2019). 'Recuperation of regenerative braking energy in electric rail transit systems', *IEEE Transactions on Intelligent Transportation Systems* 20(8): 2831-2847.

[111] Singh, V. (2017). 'Efficient utilisation of regenerative braking in railway operations', *International Research Journal of Engineering and Technology* 4(12): 1421-1428

[112] Clément, P., L. Adamczak, A. Maistre, F. Ghozzi and V. Nicot (2019). 'First experimentation of a device collecting at source airborne particles issued from rolling stocks brakes systems', *World Congress on Railway Research (WCRR) 2019*, Tokyo, Japan.

[113] Soleimani, H., and M. Moavenian (2017). 'Tribological aspects of wheel–rail contact: A review of wear mechanisms and effective factors on rolling contact fatigue', *Urban Rail Transit* 3(4): 227-237.

A significant chemical component of particulates in both of the above sources is iron oxides (with between approximately half to two thirds of total particulate content depending on study and location/assumptions). It is not possible to simply allocate to a specific source according to the particulate chemistry and this applies in many other cases too. Although complex analysis could yield relatively accurate allocations, studies have usually failed to collect sufficient data to do this (e.g. not analysing brake pad chemistry despite knowing the rail, wheel and brake disc steel chemistry)[114, 115, 116].

Table 24 Sources and chemistry of abrasive origin rail particulates

			Particle Chemistry								
Source Type		Proportion of total rail non-combustion PM (*if applicable)	Iron Oxides	Transition Metal Oxides	Aluminium Oxides	Calcium Oxide	Silicon Oxides	Copper Oxide	Elemental Carbon	Organic Carbon	Other
Wheel - Rail interface	Wheel	47-66%	Y	Y							
	Rail		Y	Y							
Braking	Friction braking - Brake discs		Y	Y							
	Friction braking - Brake pads	20-25%	Y		Y	Y	Y		Y	Y	Y
Traction motors including regenerative/rheostatic braking	Traction motors (DC)	<2%*							Y		
Overhead line equipment (OHLE)	OHLE contact wire	2.5%*						Y			
	OHLE pantograph	Not quantified							Y		
3rd/4th rail	Third/fourth rail	<10%*	Y	Y							
	Contact shoes								Y		
Flange greasing	Molybdenum disulphide grease	<3%								Y	Y
Sand application	Sand for adhesion applied to rail	Not quantified					Y				
Ballast dust	Granite break up	Not quantified			Y	Y	Y				Y

11.4 Particulate chemistry types and sources

11.4.1 Iron oxides

The main sources of iron oxides are steel in **rails, wheels, and brake discs** as well as minor sources from mineral fillers (e.g. mica) in **brake pads**. Overall, the sources total between 47%[117] and 67%[118] of total rail origin particulate content depending on study[119].

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[114] Seaton, A., J. Cherrie, M. Dennekamp, K. Donaldson, J.F. Hurley and C.L. Tran (2005). 'The London Underground: Dust and hazards to health', *Occupational & Environmental Medicine* 62(6): 355-362.

[115] Martins, V., T. Moreno, L. Mendes, K. Eleftheriadis, E. Diapouli, C. A. Alves, M. Duarte, E. de Miguel, M. Capdevila, X. Querol and M.C. Minguillón (2016). 'Factors controlling air quality in different European subway systems', *Environmental Research* 146: 35-46.

[116] Querol, X., T. Moreno, A. Karanasiou, C. Reche, A. Alastuey, M. Viana, O. Font, J. Gil, E. de Miguel and M. Capdevila (2012). 'Variability of levels and composition of PM_{10} and $PM_{2.5}$ in the Barcelona metro system', *Atmospheric Chemistry and Physics* 12(11): 5055-5076.

[117] Chow, J.C., D.H. Lowenthal, L.-W.A. Chen, X. Wang and J.G. Watson (2015). 'Mass reconstruction methods for $PM_{2.5}$: a review', *Air Quality, Atmosphere, & Health* 8(3): 243-263.

[118] Seaton, A., J. Cherrie, M. Dennekamp, K. Donaldson, J.F. Hurley and C.L. Tran (2005). Occupational & Environmental Medicine 62(6): 355-362.

[119] Smith, J.D., B.M. Barratt, G.W. Fuller, F.J. Kelly, M. Loxham, E. Nicolosi, M. Priestman, A.H. Tremper, D.C. Green (2020). '$PM_{2.5}$ on the London Underground', *Environment International* 134: 105188.

11.4.2 Transition metal oxides

The main source of transition metal oxides is from the alloying element content in the high-quality steels used in **rails, wheels, brake discs** but not the steel filler material in brake pads. As such it is it is good marker for monitoring high quality steel wear[120]. The only component likely to have any potential pollution health impacts is chromium, as the concentration of other elements is very significantly below any occupational health exposure limits in open air[121]. Hence a more detailed analysis of rail chromium emissions should be undertaken. The detailed nature of the chromium in rail particulates is not well understood and this will have a large effect on whether there are potential health implications. Its presence as non-soluble oxides would make it more inert than in the forms examined in toxicity studies to set occupational exposure limits[122].

11.4.3 Aluminium, calcium and silicon oxides

Aluminium, calcium and silicon oxides originate from minerals used in three rail applications:

- Filler materials used in **brake pads** mainly calcium hydroxide, calcium carbonate, alumina and mica[123].
- **Sand application** to enhance wheel grip during poor rail head conditions and is crushed between wheel and rail - silicon dioxide[124].
- Dust formed as the **granite ballast** gradually degrades with use over time, producing particles with high of silica and alumina content. This is only really a problem during engineering work when the ballast is replaced or disturbed and is already addressed though occupational health measures for those undertaking the work[125, 126] as can be seen in Figure 60 and Figure 61 .

Recent in-tunnel studies estimated the calcium oxide level is around 8% of particulate content and aluminium oxides is around 2%[127].

Figure 60 Network Rail photograph showing silica and alumina dust generated from

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[120] Borgese, D. (2018). Personal communication in https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/769884/COMEAP_TfL_Statement.pdf

[121] http://archive.defra.gov.uk/environment/quality/air/airquality/panels/aqs/documents/metals-and-metalloids.pdf

[122] http://www.hse.gov.uk/pubns/books/eh40.htm

[123] Blau, P.J. (2001). *Compositions, functions, and testing of friction brake materials and their additives*. Oak Ridge National Laboratory for U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Transportation Technologies.

[124] Purcell, L. and A. Lightoller (2018). *T1107: Trial of sander configurations and sand laying rates*. RSSB.

[125] Lorenzo, R., R. Kaegi, R. Gehrig and B. Grobéty (2006). 'Particle emissions of a railway line determined by detailed single particle analysis', *Atmospheric Environment* 40(40): 7831-7841.

[126] Gehrig, R., M. Hill, P. Lienemann, C.N. Zwicky, N. Bukowiecki, E. Weingartner and B. Buchmann (2007). 'Contribution of railway traffic to local PM_{10} concentrations in Switzerland', *Atmospheric Environment* 41(5): 923-933.

[127] Smith, J.D., B.M. Barratt, G.W. Fuller, F.J. Kelly, M. Loxham, E. Nicolosi, M. Priestman, A.H. Tremper, D.C. Green (2020). '$PM_{2.5}$ on the London Underground', *Environment International* 134: 105188.

handling granite ballast

Figure 61 Network Rail photographs showing various types of face mask or ventilator used when handling ballast

11.4.4 Copper oxide

The only significant source of copper oxide particles is **overhead electrification contact wire** wear. Tunnel studies in fully electric service areas with intensive services indicate copper oxide particle content is around 2.5% of the total in those locations[128].

11.4.5 Elemental carbon

There are several elemental carbon sources depending on the operating conditions:

- **Brake pad** filler compounds and brake pad modified resins[129]
- **Traction motor brushes** in the case of DC traction motors (which are being phased out)[130]
- Third/fourth rail **contact shoe** (graphite)[131]

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[128] Loxham, M., M.J. Cooper, M.E. Gerlofs-Nijland, F.R. Cassee, D.E. Davies, M.R. Palmer and D.A.H. Teagle (2013). 'Physicochemical characterization of airborne particulate matter at a mainline underground railway station', *Environmental Science & Technology* 47(8): 3614-3622.

[129] Blau, P.J. (2001). *Compositions, functions, and testing of friction brake materials and their additives*. Oak Ridge National Laboratory for U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Transportation Technologies.

[130] Borgese, D. (2018). Personal communication in https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/769884/COMEAP_TfL_Statement.pdf

[131] Loxham, M., M.J. Cooper, M.E. Gerlofs-Nijland, F.R. Cassee, D.E. Davies, M.R. Palmer and D.A.H. Teagle (2013). 'Physicochemical characterization of airborne particulate matter at a mainline underground railway station', *Environmental Science & Technology* 47(8): 3614-3622.

- Overhead line equipment **pantograph contact/wear strip** (graphite)[132]

While there have not been any detailed studies on the relative importance of these sources, brake pad filler and resin material are the biggest source given overall brake pad wear rates. Tunnel studies in fully electric service areas with intensive services show elemental carbon particle content at around 7% of the total in those locations[133].

Most abrasion PM is deposited relatively quickly because of its high density. The example in Figure 62 clearly shows accumulation of pantograph wear material on top of carriages (an area not reached by carriage washers). The top unit does not have a pantograph (3rd rail-only supply) while the bottom unit does have a pantograph with the location of the pantograph contact area shown in red. The deposition of a mixture of graphite and copper particles on the roof within ~10 m of the pantograph strip can be clearly seen.

Figure 62 Photograph of roofs of two London Overground Class 378 electric multiple units, visually highlighting the effect of graphite and copper mixture lost from the pantograph wear strip (dark grey areas on lower train)

11.4.6 Organic carbon

There are two main organic carbon sources:

- **Brake pad resin** materials (e.g. phenolic resins), which is the main source[134, 135]
- Grease, especially that used for wheel flange **lubrication**, which is a minor source[136]

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[132] Smith, J.D., B.M. Barratt, G.W. Fuller, F.J. Kelly, M. Loxham, E. Nicolosi, M. Priestman, A.H. Tremper, D.C. Green (2020). 'PM$_{2.5}$ on the London Underground', *Environment International* 134: 105188.

[133] Loxham, M., M.J. Cooper, M.E. Gerlofs-Nijland, F.R. Cassee, D.E. Davies, M.R. Palmer and D.A.H. Teagle (2013). 'Physicochemical characterization of airborne particulate matter at a mainline underground railway station', *Environmental Science & Technology* 47(8): 3614-3622.

[134] Chan, D., and G.W. Stachowiak (2004). 'Review of automotive brake friction materials', *Proceedings of the Institute of Mechanical Engineers, Part D: Journal of Automobile Engineering* 218(9): 953-966.

[135] Blau, P.J. (2001). *Compositions, functions, and testing of friction brake materials and their additives*. Oak Ridge National Laboratory for U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Transportation Technologies.

[136] Loxham, M., M.J. Cooper, M.E. Gerlofs-Nijland, F.R. Cassee, D.E. Davies, M.R. Palmer and D.A.H. Teagle (2013). 'Physicochemical characterization of airborne particulate matter at a mainline underground railway station', *Environmental Science & Technology* 47(8): 3614-3622.

Tunnel studies show organic carbon particle content at around 9% of the total in those locations[137].

11.4.7 'Unidentified'

Many studies have analysed up to a maximum of 12 chemistries of particulates, leaving up to 20% of PM as 'unidentified'. This fraction is believed to contain a number of harder to identify particles, many of which originate in brake pad material especially mineral fillers. The identification of these would be made easier if the brake pad composition was also analysed in detail.

11.5 Towards emission estimates

Abrasion particulate emissions will vary based on local factors that control abrasion wear rates e.g. friction braking and track geometry. Therefore, whilst a general factor per unit distance is suitable for most sources this should also be combined with an additional local factor for friction braking which can be fairly easily assessed based on typical train stopping patterns and whether rheostatic/regenerative braking is used.

Two estimation techniques were used in this project. The first using rail abrasion factors from the German national emissions inventory and the second using a bottom up approach calculating the total volume and mass of material removed between equipment replacement and the volume and mass of material during abrasion.

11.5.1 Estimates based on German g/km emission factors

For the first estimation technique, crude rail abrasion emission factors on a g/vehicle-km basis developed by Deutsche Bahn (DB)[138], was applied to GB rail network usage using train vehicle mileage data from ORR[139], DfT's Rail Emissions Model and NAEI calculations. Direct simple comparisons between GB and Germany are not possible as the rail networks are very different. In Germany:

- the annual train vehicle-km total is around 3 times higher
- the share of the network electrified is 1/3 higher (all high traffic density routes in Germany are electrified)
- the route distance is around 2.5 times greater than the entire GB route distance
- the proportion of electric freight haulage is far higher
- around 90% of German train vehicle mileage is electrically powered (annual German rail traction electricity usage at 27.5 TWh is 6.7 times greater than the UK at 4.1 TWh).

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[137] Smith, J.D., B.M. Barratt, G.W. Fuller, F.J. Kelly, M. Loxham, E. Nicolosi, M. Priestman, A.H. Tremper, D.C. Green (2020). '$PM_{2.5}$ on the London Underground', *Environment International* 134: 105188.

[138] Umweltbundesamt (German Environment Agency) (2020). *German Informative Inventory Report*. https://iir-de.wikidot.com/1-a-3-c-railways

[139] https://dataportal.orr.gov.uk/statistics/usage/freight-rail-usage-and-performance/

Table 25 contains the German g/vehicle-km abrasion emission factors for $PM_{2.5}$, PM_{10}, TSP, chromium, copper and nickel. For the German emissions inventory, the $PM_{2.5}$:PM_{10} ratio was assumed to be 50% and the PM_{10}:TSP ratio was assumed to be 100%.

Table 25 German g/vehicle-km abrasion emission factors for $PM_{2.5}$, PM_{10}, TSP, chromium, copper and nickel

g/vehicle-km	**$PM_{2.5}$**	**PM_{10}**	**TSP**	**Cr**	**Cu**	**Ni**
OHLE contact wire	0.00016	0.00032	0.00032	-	0.00033	-
Wheels on rails	0.009	0.018	0.018	-	-	-
Braking system	0.004	0.008	0.008	0.00008	-	0.00016

Table 26 contains GB rail abrasion PM estimates using the DB emission factors in Table 25 for passenger (diesel and electric traction), freight (diesel and electric traction) and total.

Table 26 Annual abrasion PM estimates (in kg) for GB rail sources using DB emission factors

kg per annum	**$PM_{2.5}$**	**PM_{10}**	**TSP**	**Cr**	**Cu**	**Ni**
Total abrasion	**64,255**	**128,509**	**128,509**	392	1,080	784
GB passenger	**55,938**	**111,877**	**111,877**	341	1,055	682
GB passenger - diesel	**13,857**	**27,713**	**27,713**	85	-	171
GB passenger - electric	**42,082**	**84,163**	**84,163**	256	1,055	512
GB freight	**8,316**	**16,633**	**16,633**	51	25	102
GB freight - diesel	**7,317**	**14,635**	**14,635**	45	-	90
GB freight - electric	**999**	**1,998**	**1,998**	6	25	12

Table 27 contains the estimated split between combustion and abrasion PM for GB diesel-powered trains (combustion estimates from the NAEI, abrasion estimates from Table 26 above). For both passenger and freight diesel-powered trains, combustion is the dominant source of emissions (91% and 89%, respectively).

Table 27 Comparison of annual combustion and abrasion PM estimates for GB diesel-powered trains

	kg per annum	**Proportion**
GB passenger - diesel - combustion	283,000	91%
GB passenger - diesel - abrasion	27,713	9%
GB passenger - diesel - total	310,713	100%
GB Freight - diesel - combustion	114,000	89%
GB Freight - diesel - abrasion	14,635	11%
GB Freight - diesel - total	128,635	100%

Table 28 contains estimated split between all GB (passenger, freight and total) train combustion and abrasion PM (combustion estimates from NAEI, abrasion estimates from Table 26 above). Despite including abrasion emission from electric trains for both passenger and freight diesel powered trains combustion is the dominant source of emissions (72% and 87%, respectively).

Table 28 Comparison of annual combustion and abrasion PM estimates for all GB trains

	kg per annum	**Proportion**
GB passenger - diesel - combustion	283,000	72%
GB passenger - all - abrasion	111,877	28%
GB passenger - total	394,877	100%
GB Freight - diesel - combustion	114,000	87%
GB Freight - all abrasion	16,633	13%
GB Freight - total	130,633	100%

From this analysis, it can be concluded that until there is substantial electrification of the GB rail network, combustion emission will remain the dominant PM source for the next decade and probably longer.

11.5.2 Bottom-up estimates

For the second estimation technique, data was gathered for mass lost from wear in four significant categories that make up 65-90% of abrasion emissions:

- rail wear
- wheel wear
- brake disc wear (applies to all DMUs except Classes 153, 155 and 156, and to all EMU classes)
- brake pad/block wear.

The quantification approach taken considers:

- number of wheels by rolling stock type (e.g. EMU with regenerative/rheostatic braking)
- average wear rates (e.g. an average brake disc lasts 1.1 million miles with known average mass lost)
- average annual mileage (accounting for all distance travelled as well as distance travelled while braking).

Information from TOCs and ROSCOs was gathered for:

- brake pad replacement interval
- brake pad mass: new and removed
- wheel lathe material removal
- wheel life.

Information was obtained from Network Rail on rail replacement and recycling rates, and on rail grinding. A GB rolling stock database was used to estimate axle counts.

11.5.2.1 Rail wear

In recent years Network Rail typically uses around 95,000 tonnes of new rail and scraps around 93,000 tonnes of rail each year. Since this is primarily for replacing existing track, this theoretically leaves a maximum 2,000 tonnes that could have been lost as abrasive wear. However, as discussed earlier (Section 11.2) only a small percentage of these wear particles is small enough to then be entrained in the atmosphere as TSP. Furthermore, the dense nature of the wear particles means those that are entrained then settle out comparatively quickly (compared to combustion or tyre wear PM).

However, Network Rail typically replaces older lighter cross-section rail with modern heavier cross-section rail if it has not done so previously, hence this means that the mass of new rail will often be higher than the mass of the rail being replaced when that was new. Consequently, the annual quantity of rail material that could potentially be accounted for by abrasive wear will be smaller than 2,000 tonnes.

An alternative method is to look at the maximum material the rail could have lost before replacement. However, replacement often occurs well before the allowable maximum wear for safety reasons (for example if rolling contact fatigue is present), so again this will be a conservative estimate. The upper limit for the average annual rail wear rate is just under 800 tonnes (Table 29). This is just 40% of the previous estimate of material that could be lost via abrasion based on rail replacement rates, but it is still around 16 times greater than using the German g/km factors approach.

Table 29 Maximum allowable wear approach to estimating rail wear mass and comparison to the German g/km factors-based calculation

Maximum allowable wear model		
Maximum rail wear material loss in working life	kg/m	0.35
Average rail working life at replacement	years	27.3
Total Track distance	km	31,091
Total rail wear	kg/year	797,741
Average rail wear	kg/year/track km	25.7
Average rail wear	kg/year/route km	50.3
German factor TSP calculation	kg/year	44,121
German rail abrasion factor PM_{10} vs maximum allowable wear comparison	kg/year	6%

Another potential approach is to use measured rail wear rates based on train tonnage from literature[140] and apply these rates using GB traffic data to assess the average rail

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[140] Santa, J.F., A. Toro, and R. Lewis (2016). 'Correlations between rail wear rates and operating conditions in a commercial railroad', *Tribology International* 95: 5-12.

wear rate and hence the average material lost per unit distance per annum. This was done for two cases: the first in Table 30 examines a higher wear rate situation on curved track (800 m radius of curvature) and the second in Table 31 examines a lower wear rate situation on very slightly curved or straight track. In the first case (Table 30) the wear rate is around four times the calculation for Great Britain based on the German g/km factor.

Table 30 Track usage and wear rate model for a medium to high wear rate on curved track and comparison to the German g/km factors-based calculation

Track usage and wear rate model: medium high wear on curves		
Total passenger train tonne-km	Mtonne-km	141,170
Average passenger train mass	tonnes	316
Average annual passenger train tonnage per track km	Mtonne	4.54
Total passenger train tonne-km	Mtonne-km	17,390
Average freight train mass	tonnes	614
Average annual freight train tonnage per track km	Mtonne	0.6
Average annual train tonnage per track km	Mtonne	5.10
Average cross sectional area loss per Mtonne traffic	mm^2	2
Average cross sectional area loss per annum	mm^2	10.2
Average rail material loss rate per annum	kg/m	0.080
Total track distance	km	31,091
Total rail wear	kg/year	182,728
Average rail wear	kg/year/track km	5.9
Average rail wear	kg/year/route km	11.5
German factor PM_{10} calculation	kg/year	44,121
German rail abrasion factor PM_{10} vs wear rate material loss model comparison		24%

In the second case (Table 31) the wear rate is almost exactly the same as the calculation for Great Britain based on the German g/km factors. This suggests that the potential calculation route used to create the German g/km factors was based on a similar methodology (which is not publicly documented).

Table 31 Track usage and wear rate model for a low wear rate on straight track and comparison to the German g/km factors-based calculation

Track usage and wear rate model: low wear on straighter track		
Total Passenger train tonne-km	Mtonne-km	141,170
Average passenger train mass	tonnes	316
Average annual passenger train tonnage per track km	Mtonne	4.54
Total Passenger train tonne-km	Mtonne-km	17,390
Average freight train mass	tonnes	614
Average annual freight train tonnage per track km	Mtonne	0.6
Average annual train tonnage per track km	Mtonne	5.10
Average cross sectional area loss per Mtonne traffic	mm^2	0.5
Average cross sectional area loss per annum	mm^2	2.5
Average rail material loss rate per annum	kg/m	0.020
Total Track distance	km	31,091
Total rail wear	kg/year	45,682
Average rail wear	kg/year/track km	1.5
Average rail wear	kg/year/route km	2.9
German factor PM_{10} calculation	kg/year	44,121
German rail abrasion factor PM_{10} vs wear rate material loss model comparison		97%

Although these calculations using established rail wear rates are more detailed than the maximum allowable wear approach in Table 29 , they still show a large range of mass loss rates depending on assumptions about track curvature as can be seen in Table 30 and Table 31 .

This analysis shows that looking at crude material loss rates alone is likely to over-estimate actual rail PM material volume as the accuracy of the inputs and assumptions has a very large impact. Some of the material lost (mainly via plastic deformation or fatigue mechanisms rather than normal wear) also tends to be far larger than PM_{10} and due to the high density of this PM (compared to combustion or tyre rubber PM) a very limited amount of material remains suspended (typically smaller than combustion or tyre rubber PM).

This issue needs further detailed study to determine the ratio of measurable PM or TSP to total material lost. Using wear-only model data provides a much better fit to the German factors-based approach.

11.5.2.2 Wheel wear

As part of this project, a model was developed using recent UK[141], Netherlands[142] and Swedish[143] datasets along with data from TOCs to assess material lost via wheel wear and wheel lathe reprofiling during wheelset life combined with GB fleet and usage data. Like the rail case there are many material loss mechanisms which produce a range of size particles. Wheelset life is defined by the need to both remove fatigue cracks and reprofile the wheel so it handles correctly especially with flange wear rates typically being an order of magnitude higher than tread wear. This means that majority material (around three quarters) removed from the wheel set during its working life occurs on a wheel lathe in depot rather than in use on the track due to the need to remove early stage fatigue cracks before they reach critical size and to restore the correct wheel profile. As with rail wear, wheel wear occurs very unevenly across the network with far greater wear on tighter radius curves with elevated flange wear. The results of this modelling are shown in Table 32 and Table 33 . The difference between the simple and detailed approaches to accounting for wheel profile change during use show that with the detailed approach the estimated volume of material via wear is under half than based on more simplistic approach.

Table 32 Estimates of wheel material loss via wear during wheel set working life based on simplistic analysis of wear and wheel turning cycles and mileages

Wheel - simple wear material loss		
Average material loss rate	g/km	0.0523
Average material loss rate	kg/Mkm	52.3
Annual GB material loss rate using this method	tonnes	1580
Proportion of wear of total material lost	%	53%
Annual GB material loss rate using German abrasion factors	tonnes	44
German abrasion factors approach : This method	%	3%

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[141] Muhamedsalih, Y., J. Stow and A. Bevan (2019). 'Use of railway wheel wear and damage prediction tools to improve maintenance efficiency through the use of economic tyre turning', *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit* 233(1): 103-117.

[142] Dirks, B. (2019). 'Simulation and measurement of wheel on rail fatigue and wear', Doctoral Thesis, KTH Royal Institute of Technology, Stockholm.

[143] Olofsson, U., Y. Zhu, S. Abbasi, R. Lewis and S. Lewis (2013). 'Tribology of the wheel-rail contact – aspects of wear, particle emission and adhesion', *Vehicle System Dynamics* 51: 1091-1120.

Table 33 Estimates of wheel material loss via wear during wheel set working life based on detailed analysis of wear and wheel turning cycles and mileages

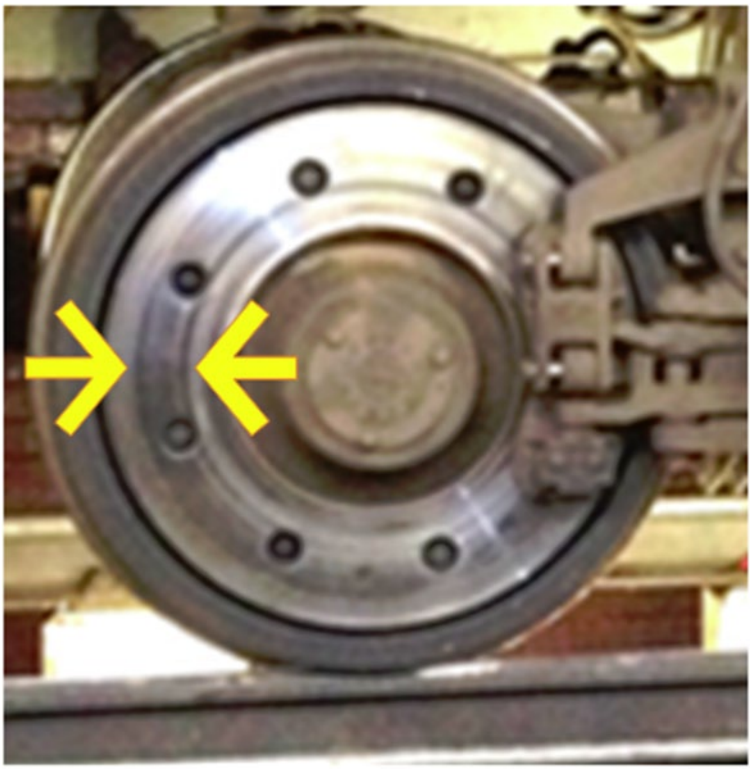
Wheel - detailed profile analysis wear material loss		
Average material loss rate	g/km	0.02578
Average material loss rate	kg/Mkm	25.8
Annual GB material loss rate using this method	tonnes	779
Proportion of wear of total material lost	%	24%
Annual GB material loss rate using German abrasion factors	tonnes	44
German abrasion factors approach : This method	%	6%

As with rail wear the maximum material lost analysis sees far higher volumes of material lost than using the German factors approach or PM concentrations from tunnel studies. Further detailed study to create a ratio of PM or TSP to total material lost is needed for this to be a useful estimation approach.

11.5.2.3 Brake wear

Most GB rolling stock is fitted with disc brakes and pads, while a minority is fitted with tread brakes (most locomotives and a limited number of older DMUs and freight wagons). The majority of GB passenger rolling stock is also fitted with regenerative or rheostatic braking that reduces the use of friction braking. This leads to a reduction in average pad wear rate (on a per km basis) of a minimum of 3.25 times and a reduction in disc wear rate of a minimum of 2.2 times compared to friction braking based on our analysis of TOC and OEM data on component life. Hence taking account of regenerative or rheostatic braking use has a large effect on estimates of braking material loss rates. Disc wear rates vary significantly across the radius of the disc (up to three-fold; see Figure 63), hence the useful life of the disc and therefore correspondingly of the pads is defined by the area of highest wear with significant material remaining in other areas of the disc and pads at replacement.

Figure 63 Annotated photograph showing the highest wear area of brake disc between the arrows



Models were developed during this project using multiple TOC and OEM datasets combined with GB fleet and usage data to assess material lost via brake pad and disc wear. Only limited data was available for tread brakes, so all disc brake usage was assumed for this analysis. Some operators also reprofile the discs on wheel lathes when wheel sets are being reprofiled so the real loss rate could be lower than the maximum material loss rate. Some of the outputs of this model are seen in Table 34 , Table 35 , Table 36 and Table 37 for brake disc wear, and Table 38 and Table 39 for brake pad wear.

Table 34 Simple analysis of maximum material lost from brake discs during working life assuming all friction braking

Brake Disc - maximum material lost - friction only braking		
Average material loss rate	g/km	0.00775
Average material loss rate	kg/Mkm	7.8
Annual GB material loss rate using this method	tonnes	234
Annual GB material loss rate using German abrasion factors for all braking	tonnes	39.2
German abrasion factors approach : This method	%	17%

Table 35 Simple analysis of maximum material lost from brake discs during working life assuming a mix of friction and rheostatic or regenerative braking

Brake Disc - maximum material lost - regenerative rheostatic braking fitted		
Average material loss rate	g/km	0.00352
Average material loss rate	kg/Mkm	3.5
Annual GB material loss rate using this method	tonnes	106
Annual GB material loss rate using German abrasion factors for all braking	tonnes	39.2
German abrasion factors approach : This method	%	37%

Table 36 Detailed analysis of material lost assuming real uneven wear patterns from brake discs during working life and all friction braking

Brake Disc - uneven wear material lost - friction only braking		
Average material loss rate	g/km	0.00388
Average material loss rate	kg/Mkm	3.9
Annual GB material loss rate using this method	tonnes	117
Annual GB material loss rate using German abrasion factors for all braking	tonnes	39.2
German abrasion factors approach : This method	%	33%

Table 37 Detailed analysis of material lost assuming real uneven wear patterns from brake disc during working life and a mix of friction and rheostatic or regenerative braking

Brake Disc - uneven wear material lost - regenerative rheostatic braking fitted		
Average material loss rate	g/km	0.00176
Average material loss rate	kg/Mkm	1.8
Annual GB material loss rate using this method	tonnes	53
Annual GB material loss rate using German abrasion factors for all braking	tonnes	39.2
German abrasion factors approach : This method	%	74%

Table 38 Detailed analysis of maximum material lost from brake pads during working life assuming real uneven wear patterns and all friction braking

Brake Pad - uneven wear material lost - friction only braking		
Average material loss rate	g/km	0.02433
Average material loss rate	kg/Mkm	24.3
Annual GB material loss rate using this method	tonnes	735
Annual GB material loss rate using German abrasion factors for all braking	tonnes	39.2
German abrasion factors approach : This method	%	5%

Table 39 Detailed analysis of maximum material lost from brake pads during working life assuming real uneven wear patterns and a mix of friction and rheostatic or regenerative braking

Brake Pad - uneven wear material lost - regenerative / rheostatic braking fitted		
Average material loss rate	g/km	0.01084
Average material loss rate	kg/Mkm	10.8
Annual GB material loss rate using this method	tonnes	327
Annual GB material loss rate using German abrasion factors for all braking	tonnes	39.2
German abrasion factors approach : This method	%	12%

In the next step of analysis, the relative use of different types of braking and relative mileages in the GB fleet was estimated to derive an annual total for brake wear material. The results of these estimates are shown below in Table 40 , Table 41 , Table 42 and Table 43 along with a summary in Table 44 .

Table 40 Estimate of brake disc wear material loss from friction only braking fleets

Brake Disc - uneven wear material lost - friction only braking		
Average material loss rate	g/km	0.00388
Average material loss rate	kg/Mkm	3.9
Annual GB material loss rate using this method	tonnes	42
Annual GB material loss rate using German abrasion factors for all braking	tonnes	39.2
German abrasion factors approach : This method	%	94%

Table 41 Estimate of brake disc wear material loss from mixed friction and rheostatic or regenerative braking fleets

Brake Disc - uneven wear material lost - regenerative rheostatic braking fitted		
Average material loss rate	g/km	0.00176
Average material loss rate	kg/Mkm	1.8
Annual GB material loss rate using this method	tonnes	34
Annual GB material Loss rate using German abrasion factors for all braking	tonnes	39.2
German abrasion factors approach : This method	%	115%

Table 42 Estimate of brake pad wear material loss from friction only braking fleets

Brake Pad - uneven wear material lost - friction only braking		
Average material loss rate	g/km	0.02433
Average material loss rate	kg/Mkm	24.3
Annual GB material loss rate using this method	tonnes	263
Annual GB material loss rate using German abrasion factors for all braking	tonnes	39.2
German abrasion factors approach : This method	%	15%

Table 43 Estimate of brake pad wear material loss from mixed friction and rheostatic or regenerative braking fleets

Brake Pad - uneven wear material lost - regenerative / rheostatic braking fitted		
Average material loss rate	g/km	0.01084
Average material loss rate	kg/Mkm	10.8
Annual GB material loss rate using this method	tonnes	210
Annual GB material loss rate using German abrasion factors for all braking	tonnes	39.2
German abrasion factors approach : This method	%	19%

Table 44 Estimate of brake disc and pad wear material loss and comparison with the German factors-based approach for brake PM

Total Braking (fleet mix)		
Brake Disc - non regenerative/ rheostatic braking	tonnes	42
Brake Disc - regenerative/ rheostatic braking	tonnes	34
Brake Pad - non regenerative/ rheostatic braking	tonnes	263
Brake Pad - regenerative/ rheostatic braking	tonnes	210
Total	**tonnes**	**549.0**
Annual GB material loss rate using German abrasion factors	tonnes	39.2
German abrasion factors approach : This method	%	7%
Average annual mass per route km	kg/km	34.6

As with rail and wheel wear the maximum material lost analysis for braking sees far higher volumes of material lost than using the German factors approach for PM or PM concentration measurement from tunnel studies.

For rail, wheel and brake wear, a detailed material loss estimate of the volume of material lost is in a range of 14 to 18 times the German PM factors-based estimates for those categories. This gives an initial estimate for the ration of measured PM to actual material loss estimates. Further detailed study to create a ratio of PM or TSP to total material lost is needed for this to be a useful estimation approach.

11.6 General findings

Rail particulate emissions of abrasion origin make up a much smaller fraction of all rail emissions compared to the abrasion-related emissions from road transport. There is very little broad high-quality work on rail abrasion particulates in non-enclosed environments. The main focus in broad studies has been the larger source of combustion emissions. The abrasion aspect has only been covered in detail in narrow single aspect studies.

Many of the most informative studies of rail abrasion emissions are in-tunnel studies with fully electric services and hence no combustion emissions present and limited road/general background levels. Some studies also compare rail particulate emissions in tunnel and in open air, with open-air concentrations being at worst around 5% of in-tunnel concentrations when measured at very close proximity to trains (e.g. on platforms) with dispersion of the particles significantly reducing local concentrations near the sources.

PM quantification is generally based on mass and limited attention has been paid to density. Because of the much higher iron component and consequently higher density of rail non-combustion emissions, it is difficult to simply compare these emissions with rail combustion emissions.

High density particles from abrasion sources settle quicker and travel shorter distances. Although such emissions are mostly iron-based, there are a range of other components with chromium being of the highest theoretical concern and flagged for future investigation in several tunnel particulate studies in the UK and Europe.

Rail particulate studies have not looked at chromium chemistry and toxicity in detail, and usually use the most 'pessimistic' values on a precautionary basis due to their limited scope. However, in other detailed work on chromium toxicity from industrial abrasion sources for occupation exposure limits (e.g. in the steel industry), the expected chemistry and valance state of chromium from rail abrasion sources, i.e. as non-soluble chromium (III) oxides, would make it more inert than in the forms assumed on a precautionary basis in rail studies, i.e. chromium (VI) oxides.

The EU has only set daily occupation exposure limits for chromium (VI) oxides (25 µg/m^3)[144] as they are viewed as far higher risk than chromium (III) or metallic chromium for which no limits have been set so far. Therefore, many European studies use the chromium (VI) occupational exposure limit in the absence of any EU chromium (III) or chromium (metallic) data or limits.

The US has set exposure limits for metallic chromium (1000 µg/m^3)[145], insoluble chromium compounds (1000 µg/m^3), chromium (III) oxides (25 µg/m^3) and chromium (VI) oxides (5 µg/m^3). The US chromium (VI) oxides occupational exposure limit is 5 times lower than the European one, but the European chromium (VI) occupational exposure limit is 10 times lower than the US chromium (III) limit or 40 times lower than the US metallic chromium limit. Hence if the US chromium (III) or metallic chromium occupational exposure limit is used instead of the European chromium (VI) occupational exposure limit, then measured chromium levels (a maximum of 1.7 µg/m^3 on the London Underground[146], a range of 0.022-0.6 µg/m^3 in a number of subway systems[147]) are well below this limit.

Overall then, abrasion emissions are not significant to human health unless in extended direct proximity which only occurs during some maintenance activities. Network Rail and its contractors have undertaken extensive work on occupational health exposures to identify relevant mitigation measures.

A quantification of national abrasion emissions from rail has set these emissions in context against all rail emissions. This quantification approach will enable future evaluation of spatial variations in abrasion emissions, for instance, taking account of expected higher levels in areas with friction braking, such as entries to stations.

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[144] https://www.hbm4eu.eu/the-substances/chromium-vi/

[145] https://www.atsdr.cdc.gov/csem/csem.asp?csem=10&po=8

[146] Smith, J.D., B.M. Barratt, G.W. Fuller, F.J. Kelly, M. Loxham, E. Nicolosi, M. Priestman, A.H. Tremper, D.C. Green (2020). 'PM$_{2.5}$ on the London Underground', *Environment International* 134: 105188.

[147] Abbasi, S., A. Jansson, U. Sellgren and U. Olofsson (2013). 'Particle emissions from rail traffic: A literature review', *Critical Reviews in Environmental Science and Technology* 43(23): 2511-2544.

12 Conclusions and recommendations

12.1 Conclusions

There are number of limitations with previous GB rail emission factors that restrict their application to addressing current air quality issues. These include their inability to account for varied drive cycles and granular differences in operating modes, unclear data sources, conservative assumptions and proxies, recent changes in fuel quality, and the recent introduction of many types of new rolling stock.

This report documents a methodology that has been used to develop emission factors by notch (in units of g/kWh) for a large majority of current locomotive and DMU classes, covering over 90% of the GB fleet by 2018 diesel usage. This approach has been well established in the US and elsewhere and it enables effective evaluation of diesel rolling stock performance in all engine operating modes against current emission standards.

These new g/kWh emission factors have been combined with real world drive cycle data to improve the current NAEI emission factors (which are in units of g/train-km or g/vehicle-km). This has already yielded a more accurate picture of the rail sector's contribution to national emissions totals from all sectors.

The new emission factors have been combined with detailed OTMR data and train loading data to evaluate emission scenarios, i.e. to understand the sensitivity of rail emissions to operational and infrastructure requirements and restrictions. This work was carried out as part of this project and is the subject of a separate report[148].

More meaningful modal environmental comparisons can be made using g/tonne-km derived from the new factors. They can also be used to better understand local air quality issues, especially where there is a prevalence of low speeds and idling combined with limited dilution of air pollutants.

The new factors can also be used to improve the REM model or evaluations of the spatial distribution of rail emissions by using more accurate factors for each type of rolling stock and service pattern. They can also be used to benchmark current emissions during the evaluation of investment cases for emissions mitigation solutions such as OEM and third-party modifications, as well as for infrastructure improvements.

Emission factors by notch inherently permit an understanding of emissions at a granular level and so the exact impact of measures under different engine operating conditions can be determined rather than meeting a single average emission standard that may obscure the importance of high emissions in certain modes. This is particularly relevant to assessing whether emissions in idle can be effectively reduced. Specific upgrade

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[148] Mansell, G., R. Brook, N. Grennan-Heaven and M. Gibbs (2020). *T1187 CLEAR: Fleet wide assessment of rail emissions factors – Emission scenarios report*. RSSB.

pathways can be evaluated for their emission impacts as well as capital and operating costs (maintenance, fuel consumption).

Most previous studies of rail non-combustion emissions are focused on one specific type of abrasion such as brake wear or sand application. In general, particle sizes from such processes are very small, <0.1 µm, compared to rail combustion emissions. The most important type of particle emitted in terms of chemistry are iron oxides, mainly from brake disc, wheel and rail wear. Other sources of particulate emissions are brake pads, electrical contacts with third and fourth rails or overhead wires, and the breakdown of granite ballast beneath the rails.

Abrasion emissions from GB rail are less significant than combustion PM emissions but as a proportion of total rail emissions will rise with increasing electrification. Some studies show that open air PM concentrations are at most around 5% of in-tunnel concentrations when measured at very close proximity to trains. This indicates that dispersion of the particles significantly reduces local concentrations near the sources. Health concerns from abrasion PM are only likely to be significant for maintenance workers but this risk is well understood and mitigated.

12.1.1 Implications for emission reduction strategies

Reducing combustion emissions requires a detailed and accurate understanding of the conditions under which emissions are produced in order to select the best mitigation strategy. There are two main categories of potential reduction strategies that essentially mirror the two elements of the emissions estimation methodology (activity and emission factors):

1. reducing engine use
2. reducing engine emissions.

The former includes aspects such as reducing time spent in idle as well as reducing transmission losses, while the later focuses on reducing production of air quality pollutants from the engine and/or abating those emissions. A very limited number of methods involve both reduction strategies.

Overall, it is important to note that no single measure will be capable of solving all rail emissions issues. A mix of engine design modifications and abatement will be required in the future to reduce rail emissions in real use, as well as extensive changes to electrical systems and how auxiliary loads are powered and controlled in order to reduce engine use in key locations.

Specific strategies are discussed in the following sections, and all of which can be meaningfully assessed using the approach developed in this project, provided relevant emissions testing and OTMR data are available. As such they can provide useful building blocks to develop and implement the RSSB air quality strategy as well as monitoring and understanding the effectiveness of such a strategy and of the RSSB decarbonisation strategy.

12.2 Strategies to reduce engine use

This category not only includes reducing total engine use (in terms of total engine running time), typically by aiming to reduce engine idle use (which often occurs in problem emission locations such as enclosed stations) but also reducing total engine power requirements and aiming to run engines in less polluting conditions.

12.2.1 Reducing engine running time in Idle

The most effective emission reduction measure is to simply reduce the amount of time the engine is running, and especially time spent in idle, where air pollutant emissions are the highest per unit of power produced compared to other engine notches. Idle accounts for between 53% and 75% of total engine running time. For passenger trains, time spent in idle in (especially, enclosed) stations is of the most concern because of the relatively high production of air pollutants in idle and because of the limited dispersion.

Often reductions to engine running time have not needed any complex engineering interventions. Some reduction of the time spent in idle is possible through revised operating practices, often reinforced by simple changes to train control systems such as adding timers that cut engines out under specific circumstances or by more complicated locomotive example AESS systems (which manage the cooling and auxiliary load requirements). While both technology solutions see greater reductions in fuel use and air quality pollutant emissions than revised operating practices, there are still significant limitations on what they can achieve as often there is a requirement to keep the engine(s) running to supply auxiliary loads. These include maintaining the pressure in air reservoirs for the braking so that the train can be ready to leave on time, or warming up the engine before it can supply high power outputs without significant engine wear. Consequently, operational practices mean that engines are only shut down when it is known the train will be idle for more than 15 minutes.

For instance, for diesel freight locomotives, AESS has now been deployed by multiple FOCs. Its usage is generally limited to known long-duration stops such as in freight terminals rather than in passing loops where brake air pressure must be maintained so the train can quickly move when it receives permission to proceed. A detailed assessment of OTMR data combined with emission factors by notch carried out as part of this project[149] will help better understand the effects of AESS in reducing local air pollution impacts around urban freight terminals.

Auxiliary loads and how they are currently provided for present a large challenge to reducing engine use in a significant proportion of the current fleet. Some loads are

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[149] Mansell, G., R. Brook, N. Grennan-Heaven and M. Gibbs (2020). *T1187 CLEAR: Fleet wide assessment of rail emissions factors – Emission scenarios report*. RSSB.

directly (mechanically) powered by the engine such as air compressors (that are used to supply the compressed air needed by braking on most multiple units and locomotives and for secondary suspension systems on multiple units). These loads are electrically powered on electric or bi-mode diesel electric rolling stock so they could theoretically be powered electrically on diesel electric rolling stock. However, the current electrical and battery system are insufficient in all but the most modern rolling stock (which has been designed and built with electrically operated compressors and other loads). Similarly, bi-mode (diesel and electrically powered) rolling stock usually has electrically powered engine pre-heating to reduce engine warm up and idle running requirements.

For diesel trains, there is currently a general trend of moving away from supplying auxiliary loads mechanically to supplying these loads electrically. For instance, a possible solution to permit earlier engine shutdowns may involve charging batteries when the engine is running that then have sufficient capacity to run compressors to maintain air brake pressure when the engine is not running.

Heating on diesel hydraulic and mechanical transmission multiple units is mostly provided using waste heat from the diesel engine(s), hence providing heating at colder times of year for DHMUs and DMMUs normally requires the engines to be kept running when a train is stationary as the alternative heating sources cannot always provide the full heating required at these times. Furthermore, often other auxiliary electrical loads such as lighting, ventilation (if applicable) and recharging of required battery reserves also need to be provided requiring the engine to be running when a train is stationary.

Bi-mode and electric transmission diesel rolling stock can also benefit from 'shore supplies', that is a plug-in mains-powered electrical connection available at limited number of relatively large but comparatively quiet termini where trains have long layover times between journeys, as well as in certain depot and stabling areas. By providing most if not all the auxiliary loads for certain passenger stock a large reduction in idle running time is possible in many cases.

12.2.2 Transmission efficiency improvements

Certain (older) types of rolling stock have relatively low transmission efficiencies under particular operating conditions and these could be theoretically improved by utilising new technologies. The result is that higher engine power would be needed for less time as the train accelerates faster due to greater tractive effort and can coast after achieving line speed for longer with some small journey time reduction benefits that could also potentially reduce total engine running time if Idle reduction measures are also implemented for when the train is stationary.

In the case of older diesel electric transmissions substantial benefits for both fuel efficiency and reduced emissions can be achieved with the use of 3-phase drives and traction motors over older technology. A direct improvement in fuel efficiency of least 7-8% results from improved tractive effort and transmission efficiency. Further benefits from reducing engine running time at higher power outputs as well as total engine running time could produce another 5-6% reduction in fuel use is some circumstances.

While there has been extensive replacement of electric multiple units traction electrical equipment in recent years (e.g. SWR Class 442 and 455, and some Greater Anglia Class 321), there has been no interest in upgrading the traction electrical equipment on either electric or diesel locomotives in the UK unlike in some other countries. For example, many US freight operators have been replacing older traction electrical equipment with modern 3-phase drives. This has been done with OEM support, initially just by EMD and more recently by Wabtec (formerly GE), and without OEM support via a variety of smaller suppliers. For instance, CAF are supplying 3-phase drives and traction motors to retraction older Indian Railways' EMD-equipped locomotives. One potential issue for following a similar approach in the UK is whether the space is available within the British loading gauge for the slightly bulkier traction electrical equipment without needing additional significant modifications.

In the case of DHMUs that are used extensively on stopping services then the potential exists to reduce fuel use as well as emissions by replacing the hydraulic transmissions with mechanical transmissions. These have substantially lower transmission losses up to around 45 mph, but slightly worse transmission efficiencies at high speeds. One potential issue with mechanical transmission is that unless a transmission type enables coasting, the overall benefit in fuel efficiency and emission reduction may be small.

For diesel rolling stock fitted with electric transmissions (including bi-modes) there is the opportunity to use battery hybrid systems as well. This potentially enables reduced engine idle running and total engine running time by allowing auxiliary loads to be powered by either batteries or regenerative braking, thus allowing the engine to be shut down in the vicinity of stations when either stationary or coasting or braking during the approaches.

If the battery and electrical systems are sufficiently powerful it could also allow the train to accelerate away from stationary in or outside stations under battery power. These integrated traction and power systems have become available for new rolling stock in the last 3-4 years but overall they need substantial modifications to existing rolling stock if being retrofitted. There are currently several separate UK trials (involving two ROSCOs, two TOCs, two groups of equipment suppliers and three sub-fleets of rolling stock) of these systems under way with modifications to DHMUs in progress to assess both how these systems perform in real use and the practicalities and cost of modifying existing rolling stock. Modifying existing rolling stock may not result in the full benefits compared to implementation on new rolling stock. The benefits of mitigating emissions incurred from congestion-related stops and accelerations outside major stations (where an approach is not smooth) are examined in the associated emission scenarios report[150] for this project.

12.2.3 Locomotive cab heating

Current batteries in freight locomotives are not sufficient to maintain electric cab heating while the engine is off. Consequently, engines are left running during engineering possession when a locomotive may be idle for an extended period of time in an urban area. It may be possible to extract heat from the engine cooling circuit even when the engine is off, a solution that is used for locomotives in Nordic countries.

12.2.4 Infrastructure improvements

In addition to onboard locomotive modifications, infrastructure modifications can reduce emissions of GHG's and air pollutants by reducing the need for freight trains to decelerate and accelerate. For instance, three-aspect banner repeaters enable less defensive driving and so preserve momentum and kinetic energy. Connected Driver Advisory Systems (C-DAS) can provide recommendations for both passenger and freight trains to optimise speeds and fuel consumption while maintaining adherence to a timetable path. Improvements to physical infrastructure include raising loop turnout speeds so allowing trains to enter a loop at higher speed and more smoothly brake within the length of the loop. Similarly, a higher speed limit to re-join the mainline allows a train to accelerate faster and more efficiently, so at least reducing local emissions, instead of proceeding at a slow pace before the last wagon has cleared the points.

12.3 Strategies to reduce engine emissions

12.3.1 Minimising production of emissions (versus abatement)

When considering emission reduction measures there should be a focus on reducing production of emissions in the first instance rather than abatement measures. However, recent emission rules have been based on the assumption that most of the required emission reductions will be achieved with abatement as not all of the required reductions can be achieved with engine modifications alone. For example the European Commission's thinking on reducing NO_x has focused around most (~90%) of the reduction coming from a single abatement (aftertreatment) technology solution (SCR) that is best suited to both real and regulatory drive cycles for road (including cars) and most NRMM uses. SCR also requires the use of low sulphur fuel hence it could only be introduced after fuel specification changes. The European Commission's view was that the other small amount (~10%) of NO_x reduction would come from changes to engine design. This fits with to the 15% weighting for idle in the ISO 8178:C1 drive cycle which

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[150] Mansell, G., R. Brook, N. Grennan-Heaven and M. Gibbs (2020). *T1187 CLEAR: Fleet wide assessment of rail emissions factors – Emission scenarios report*. RSSB.

is very unrepresentative of real rail engine use (see Section 3.7). Hence what is a simple effective solution for the regulatory drive cycle is far less effective in practice for real rail engine use.

Usually it is far cheaper both in capital and operating costs to reduce PM compared to NO_x while NO_x is the bigger emission problems for rail. Engine manufacturers, especially of the heavy duty NRMM engines used in rail, have taken a different view to the regulators in that it is more space and cost effective (for both user capital and operating expenditures) to have a greater focus on reducing production of emissions in the first place. This reduces or eliminates the requirement for certain abatement measures, e.g. using exhaust gas recirculation, improved air charge intercooling, improved engine cooling (split circuit), multiple/ variable geometry turbochargers and modified injection and valve timing to reduce NO_X. With less abatement needed then less SCR is needed which reduces the space required and the quantity of expensive precious or semi-precious metals needed, as well as the ongoing consumption of diesel exhaust fluid ('AdBlue', a 32.5% urea solution) needed to reduce the NO_X to nitrogen and water.

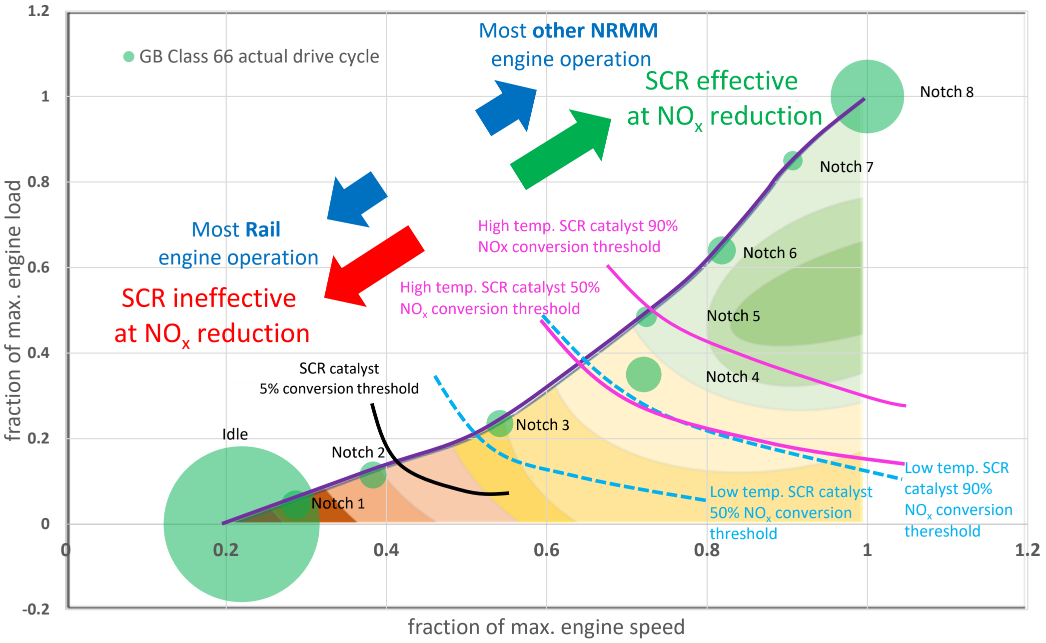
12.3.2 Abatement solutions and limitations

As regards passenger DMUs a range of emission mitigation solutions are currently being developed. These include the very bulky combined end-of-pipe solution of DOC followed by DPF and then SCR being fitted with new engines (these abatement processes are described in detail in Section 2), as well as installing electric transmissions combined with battery energy storage (essentially converting a DHMU or DMMU to a bi-mode train). All of these solutions can be evaluated by the approach developed in this project.

All three main abatement measures (DOC, DPF, SCR) only work under certain operating conditions e.g. minimum operating temperatures (in all three cases) or additionally require sufficient NO_2 for regeneration in the case of DPF. These measures tend to provide the best emission reductions at high exhaust temperature that typically correlate with high engine power outputs. Figure 64 shows the iso-catalytic conversion efficiency lines for two types of SCR technology (for a modelled Class 66 example). Note that >75% of the real drive Class 66 drive cycle is outside the effective temperature range needed for SCR to operate.

SCR is effective at removing NO_x when engine operating conditions already lead to a low intensity of NO_x generation in g/kWh (but large overall quantities of NO_x). SCR is ineffective at removing NO_x when there is a high intensity of NO_x generation (in g/kWh). Thus the proportion of NO_x emissions reduced by SCR (as a percentage of total NO_x combustion emissions by mass) is at least three quarters at higher power output conditions on newer engine designs fitted with SCR (along with other, smaller NO_x reductions due to engine design changes; upper right area in Figure 64). However, at idle and low power conditions (lower left area in Figure 64) the reduction is around a just quarter and is due to the other engine design changes not SCR.

Figure 64 SCR conversion efficiency under different engine conditions with the iso-catalytic conversion efficiency lines for two types of SCR technology (for a modelled Class 66 example)



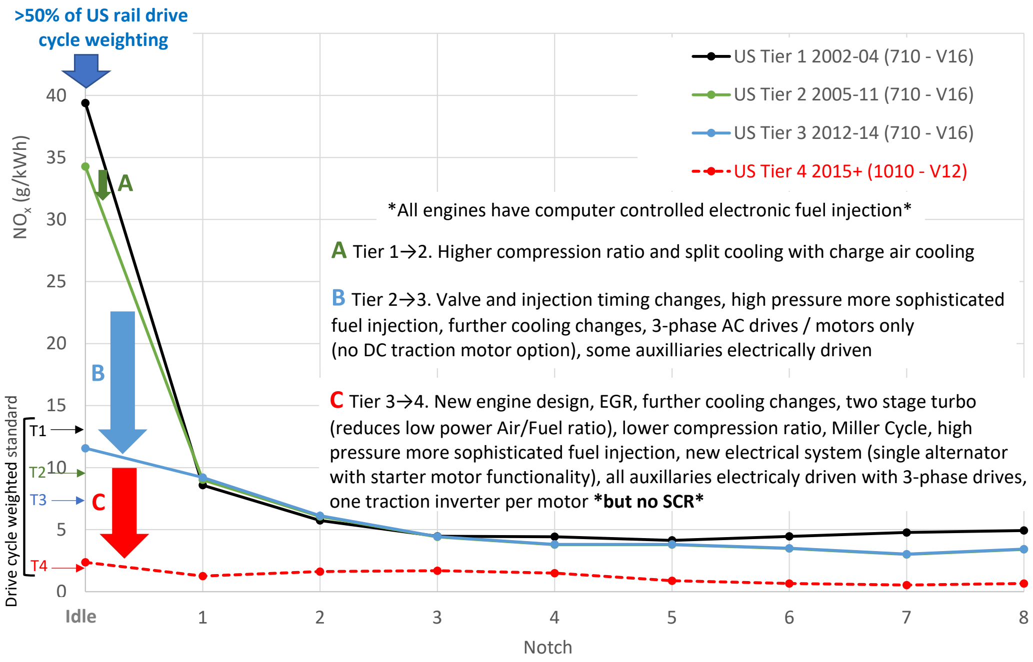
Importantly, SCR is ineffective at reducing NO$_x$ emissions at idle and low power due to the lack of required exhaust temperatures, which is a significant problem for both rail and certain other NRMM applications, e.g. excavators in real world use. DOC has similar but slightly lower temperature thresholds and is only non-functional in Idle and Notch 1 conditions.

An extreme counter example to European thinking about the primacy of abatement in reducing emissions is seen in the US where both EMD and GE have developed engines that have reduced production of pollutants to comply with the current US emission standards (Tier 4 which are stricter than Euro IIIB/V). These engines do not require SCR. Costs are just under an extra $1 million per engine with slightly reduced fuel consumption; however, the lifetime cost is lower than for SCR and AdBlue when fuel use is comparatively high. Other engine manufacturers have struck a compromise through a lower degree of reduction in pollutant reduction and some utilisation of SCR.

The US EPA's thinking is different in that in their view there was not a single technology that would produce a complete emission reduction in practice. Hence the US EPA followed a market-driven sub-sector by sub-sector approach. The US EPA thinking and the application of both their single factor mathematical weighting and realistic drive cycles also aligns with their detailed sub-sector by sub-sector approach leading to better alignment of regulatory goals and real-world operational conditions.

Figure 65 shows how EMD, a US locomotive manufacturer, adapted to changing US emissions regulations over time. The different US approaches to single factor mathematical weighting and drive cycles forces different thinking by manufacturers on how to achieve NO_x reduction and have forced the substantial reductions in NO_x between Tier 2 and Tier 4. With the majority of rail engine use being at idle or low power (and reflected in regulatory standards), technologies that reduce (rather than abate) NO_x production in those conditions need to be used, for example EGR, more sophisticated, high-pressure fuel injection, multistage turbocharging and changes to engine cooling. This different approach in the US is not just confined to rail diesel engines but also applied in other sectors such as inland marine and opencast mining. In those sectors current engines compliant with Euro Stage IIIB/V are fitted with additional technology such as EGR to comply with the different drive cycle conditions of US standards (see Section 3.4) where SCR is less effective.

Figure 65 NO_x emissions by notch for EMD engines compliant with the US Tier 1-4 emission standards and the technological steps taken to bring about reduced emissions



All engines have computer controlled electronic fuel injection

A Tier 1→2. Higher compression ratio and split cooling with charge air cooling

B Tier 2→3. Valve and injection timing changes, high pressure more sophisticated fuel injection, further cooling changes, 3-phase AC drives / motors only (no DC traction motor option), some auxilliaries electrically driven

C Tier 3→4. New engine design, EGR, further cooling changes, two stage turbo (reduces low power Air/Fuel ratio), lower compression ratio, Miller Cycle, high pressure more sophisticated fuel injection, new electrical system (single alternator with starter motor functionality), all auxillaries electricaly driven with 3-phase drives, one traction inverter per motor ***but no SCR***

12.3.3 Upgrades to existing engines

In terms of improvements to existing (older) engine designs in use to reduce production of emissions (rather than just abatement options), technologies from newer versions of these engine designs have the potential to reduce production of emissions if the newer versions meet Euro IIIA or are still in production, i.e. they comply with Euro IIIB /V.

Whether the cost of upgrade and modification is justifiable is another matter. For the GB rail industry this situation applies to just these manufacturers and engines:

- MTU - some engines (engine families where intellectual property is not shared with other manufacturers)
- EMD - 645 and 710 engines
- Cummins - QSK19 engine and limited parts for other engines
- MAN - VP185 engine (but all examples in use are soon to be retired).

Pre-existing third-party technologies and solutions may also be applicable to those not on the list above in some areas, e.g. fuel injectors/injection systems and crankcase oil mist filters. Otherwise emission reduction is largely limited to new third-party technology development or just using abatement measures which are bulky and difficult to fit in new GB rolling stock designs, let alone some older ones.

12.3.4 Engine modifications kits

As examples of the potential modifications discussed above, for the Class 66 and in many cases other freight locomotives, certain EMD solutions can be ported over from the US and sensibly applied to locomotives during major overhaul for relatively low marginal cost:

- Kits to address PM emissions are typically cheaper and easier than those to address NO_X emissions. These include oil separators (now a retrofittable design), low lube cylinder liners and rings, and installing fuel injectors used in US Tier 3-compliant engines (which provide better dispersal and control in the cylinder and result in up to a 71% reduction in PM emissions).
- Solutions to implement NO_X reductions can include potential fuel consumption penalties. Example solutions include installing fuel injectors used in US Tier 3-compliant injectors (which provide better fuel dispersal and control in the cylinder), changes to injection timing, and changes to exhaust timing up to 44% aggregate reduction in NO_X emissions. As with all fuel injection timing changes to reduce NO_x, there is a small fuel efficiency penalty.

The above percentage reductions are be based on the US drive cycle which is more representative of real GB freight operation than either ISO 8178 drive cycle. However, analysis of emissions testing data by notch could be used by the methodology discussed in this report to determine the exact expected reductions for GB drive cycles.

The simplest and cheapest emission reductions from modifications to older engines are for organic carbon PM by adding or upgrade crankcase oil mist filters, a consequence of manufacturers having had to substantially improve filtration to comply with Euro Stage IIIA or US Tier 3. There are often options from OEM and third-party suppliers to improve filtration above the minimum levels required, such as improved filtration efficiency, both for smaller oil particles (<1 µm) and under a wider range of engine operating conditions.

12.3.5 Turbo/supercharger performance at low speeds

The current Class 66 design (as with many single stage turbocharger designs) supplies too much air to the engine in most notches (under 75% of full power output) resulting in ultra-lean combustion and increased NO_X generation (around 10 times too much air is supplied at idle). Measures, such as a moveable air dam or bypass, to reduce the air boost at idle can be considered. Often newer larger NRMM engines (including for rail) have newer multistage turbo designs which have lower boost at idle and low power outputs.

12.3.6 Fuel additives/fuel hygiene

Fuel contaminants can increase the production of PM and NO_X and the use of fuel additives and adoption of better fuel hygiene procedures around fuel storage and system cleaning have been shown to reduce PM emissions by up to 15% and NO_X emissions by up to 4%[151].

An improved fossil diesel specification (requiring extra refining) to reduce the aromatic content of diesel with more hydro treatment and hydrocracking, to reduce the long chain PAHs in the fuel as Sweden has done with the MK1 diesel fuel, will also see reductions in both PM and NO_X production.

12.4 Recommendations for future work

12.4.1 Data gap filling

The BR Research Report[152] from 1994 underlies many of the current NAEI emission factors. It could be used to refine the NAEI timeseries back to 1970 for older train classes. The report has apparently not been archived and could not be located during the course of this project. It is possible that a comprehensive search of relevant industry organisation archives may be successful or relevant retired personnel may have access to a copy.

12.4.2 Broader OTMR collection

Continued compilation of OTMR data would further establish variance and expand a collection of different routes, services, loadings, and traction classes and subclasses. Acquisition of Class 57, 195/196, 755 and 800/802 OTMR data would improve the accuracy of the emission factors developed in this project for these rolling stock classes.

Further OTMR data would be needed for more detailed evaluation of modal comparisons (g/tonne-km studies), infrastructure investment cases, local urban

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[151] https://www.fuelperformancesolutionsltd.co.uk/technicalreports
[152] Wilkins (1994). *Determination of diesel exhaust emissions on British Rail*. British Rail Research, Materials Science Unit, Report LR-MSU-036.

hotspots, and more detailed spatial analysis of rail emissions. Coordination with other RSSB projects that compile OTMR data is recommended.

12.4.3 Respond to new rolling stock introductions

Recent introductions of new rolling stock include new CAF Civity DMUs (Class 195) for Northern and Stadler Flirt DMUs (Class 755) for Greater Anglia. Very limited data for these classes was acquired during this project, likely a result of TOC engineering staff having to focus on the new fleet introductions, and so proxy emission factors had to be developed. It is recommended that once these units are fully deployed then detailed data, similar to that compiled here for other classes, be obtained to determine emission factors by notch for these classes.

12.4.4 New real-world emissions testing

The engine emissions data used in this project is all based on static (test rig) testing, which is generally more accurate than dynamic (on-board) testing, particularly for larger engines such as rail engines. The approach described here of compiling and using emission factors by notch with OTMR data means that significant value can be added to emissions testing as the resulting data can be applied to a broad range of situations.

Dynamic testing may be of particular value once analysis of emissions by notch and OTMR data has identified situations that warrant further investigation. Dynamic test results can be used more broadly provided detailed testing records can be correlated with OTMR data, i.e., emissions by notch can be determined, rather than just deriving total emissions for a certain trip.

Some of the engine testing data used in this work was based on only a few data points; further real-world testing could be used to revise and improve the emission factors developed here. Another justification for further emissions testing is to properly account for the 2012 fuel specification change. Earlier testing will have been based on fuel with a higher sulphur content. A US EPA methodology is available to correct for the resulting higher PM emissions compared to those derived from low sulphur fuels, but a complicating issue is that before 2012 UK diesel was derived from different crude oil sources with differing sulphur content. Therefore, carefully documented testing with the current fuel specification is recommended.

There are limited $PM_{2.5}$ emission testing data for rail engines. This important pollutant should be included in any future testing. Nitrous oxide (N_2O) has a high GWP but is not covered directly by current emission standards and has only been studied previously on a limited basis. Future testing of rail engines should include measurement of N_2O emissions where possible.

12.4.5 Update NAEI factors

Revised NAEI emission factors in units of g/train-km or vehicle-km can be developed by combining emission factors by notch with representative drive cycles based on OTMR data that cover the distances travelled and time spent in each engine notch. Following earlier RSSB-supported work, revised g/km emission factors for the NAEI have already been developed for Classes 150-172, different HST configurations and different Class 66 subclasses. Based on the further information collected for this project, new g/km emission factors could be developed for Classes 220, 221, 222, 800 and 802. Collection of OTMR data will be needed to enable g/km emission factors to be developed for other locomotives and trains such as Classes 57, 60, 175 and 195/196.

Location of the BR Research Report from 1994[153] would also help understanding of the drive cycle used in derivation of emission factors for Classes 47 and 56 in that report (which are used throughout the NAEI time series) and whether subsequent fuel quality, operational usage and drive cycle changes should be accounted for.

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[153] Wilkins (1994). *Determination of diesel exhaust emissions on British Rail*. British Rail Research, Materials Science Unit, Report LR-MSU-036.