T1235 (CLEAR) Performance requirements and testing protocols for emissions mitigations

Methodology Report

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Executive Summary

Poor air quality is the greatest environmental risk to public health in the UK. Through the Air Quality Strategic Framework, the GB rail industry has committed to ensuring that appropriate and effective mitigation measures are taken to reduce emissions of air quality pollutants. The RSSB T1235 project set out to establish a Testing Protocol to assess the emissions benefits of various retrofit options for diesel rolling stock in a consistent manner and under test conditions which are representative of real-world usage, and to help support and prioritise investment in the most effective solutions.

This technical report describes the background and objectives of the T1235 project, and the underlying methodology and data used to develop the Testing Protocol which is published in a separate document. This report is aimed at senior industry stakeholders and technical specialists to enable them to understand the methodology behind the Testing Protocol and the issues that are critical to conducting successful rail emissions testing in a transparent manner. Consistent and complete reporting of mass-based emission testing results (and not just concentration measurements) will enable learnings to be transferred to other rolling stock types and mitigation solutions.

Regulatory engine testing is based on a fixed pre-defined drive cycle (i.e. the total proportions of time spent in particular engine modes) and focuses on a single metric (typically in g/kWh) across the complete drive cycle. However, this approach may mean that issues at particular parts of the drive cycle, such as idle, may not be addressed. It also does not reward solutions, such as battery hybrid rafts, that involve not running the rolling stock engines in key areas such as enclosed terminus stations.

The Testing Protocol proposed here requires gathering sufficient (but not unduly onerous) emissions testing data from static engine emissions testing at defined mode test points reflective of real-world usage for individual rolling stock classes. This data is then weighted based on the time in different engine operating conditions encountered during real-world running to model the emissions across the total drive cycle or for particular situations such as within stations and depots or during journeys. This granular approach provides maximum flexibility and transferability of the testing data, and can be used to determine the change in emissions between before and after the implementation of an emissions mitigation solution, including when the drive cycle is changed. It will be able to address the full range of realistic mitigation solutions applicable to GB rail. Essentially, the data can be analysed in multiple ways to understand the impact of potential emissions reductions in different situations, while enabling transparency and transferability.

The Testing Protocol is primarily aimed at older rolling stock where engines tend to have the highest emissions and are often not subject to applicable emission standards. For such rolling stock there is thus a high potential for retrofit mitigation solutions to make a substantial impact on emissions without the requirement to maintain compliance with applicable emission standards (based on regulatory testing). Different rolling stock will

have different engine and transmission characteristics. For this reason, mode test points and weightings are specified in the Testing Protocol for each train class or family, engine and vehicle maximum speed.

In current regulatory testing, it is assumed that idle conditions include a small amount of power. However, testing idle emissions when the engine supplying realistic auxiliary loads (or equivalent loads if the engine is removed from rolling stock for testing) is especially relevant for understanding air quality issues in rail locations such as stations and depots. Suitable average auxiliary loads to be used for the rolling stock are defined in the Testing Protocol.

Diesel-electric transmission and diesel-hydraulic/mechanical transmission rolling stock require different testing procedures. The former (especially locomotives) can provide testing loads when connected to a resistive load bank while the engine is installed on the rolling stock. Most diesel-electric transmission rolling stock have fixed pre-set throttle levels and engine speed control that corresponds to fixed power outputs (at a given engine speed) usually referred to as "power notches" and hereafter as notch or notches. Given the relatively constant engine running conditions in a notch, emissions are relatively constant in a given notch and a relatively small range of mode test points for emissions testing covers the entire engine operation.

Engines in diesel-hydraulic/mechanical transmission rolling stock must usually be removed and tested on a dynamometer (unless only stationary idle emissions are being measured). Such rolling stock has fixed pre-set throttle levels but does not have the combination of fixed engine speeds and power outputs of electric transmission rolling stock. Hence for each notch, emissions testing needs to be conducted for a range of engine speeds (50 rpm increments are suggested) to reflect the complex relationship between vehicle speed and engine speed for hydraulic or mechanical transmissions. For more modern engines interrogation of the engine control unit (ECU) allows the relative time spent at various engine speeds in each notch in real world use to be understood relatively easily. Audio monitoring was used during this project for the analysis of engine speed for older non-computerised engines in relevant diesel hydraulic multiple units (DHMUs) and diesel mechanical multiple units (DMMUs).

Detailed drive cycles and mode test points for the relevant rolling stock in scope were created based on the engine rpm (from the audio monitoring frequency), engine notch (from the audio monitoring relative amplitude), and train speed data from GPS. Prior on-train monitoring recorder (OTMR) data from other previous trips was used for understanding gaps in engine behaviour, aiding interpretation of notch settings and total drive cycles beyond the period of onboard audio recording. For future conditions post mitigation option installation where the test mode points and/or drive cycle weightings may change, design data for these options can be used to derive new drive cycle weightings.

For simplicity, transient conditions are excluded from the Testing Protocol because of the minimal impact they have on total emissions. The two most relevant transient conditions to address with scenarios rather than fixed test points because of their specific significance to exposure in fixed locations are cold, warm and hot starts (where emissions will be higher than normal idle after extended running); and the cooling of the exhaust system and its effect on emissions after the engine changes to idle (such as during the approach to and arrival in a station).

Emissions reduction targets for different potential mitigation solutions were considered. Using real world drive cycles for before and after any engine changes are made will usually lead to a smaller expected emissions reduction than is often claimed for mitigation solutions. This is largely due to the higher proportion of time in idle in rail compared to other sectors. At this time it is only possible to define very conservative (and so not stretching) targets for many mitigation options. Substantially more baseline data are needed to understand engine operating conditions and the potential for reductions in particular conditions encountered in rail.

Several key recommendations are made in this report:

- Testing at end of the engine's working life just before major overhaul presents a relatively simple, easy and the cheapest opportunity to gather some through-life emission testing data for both locomotive and diesel multiple unit (DMU) engines. Mid-life testing for DMU engines presents a substantial challenge because of the costs and impacts on an operator to remove and test the engine. Two potential approaches could be followed:
  - Conservatively assume a linear increase in emissions from start of working life to end of working life (the actual increase in emissions at mid-working life will be lower than this).
  - Test one or two DMU engine types at mid-working life and use the data gathered to make assumptions on other engine types.
- Make the results of at least the baseline (pre-installation of a mitigation solution) testing for a range of rolling stock widely available in a library of baseline testing results. A shared benefit would be providing understanding to all relevant parties of whether a particular mitigation solution would be suitable and effective before design and development were started.
- The issue of ensuring ongoing selective catalytic reduction (SCR) performance in rail will apply not only to retrofit systems but also to newer rolling stock where functioning SCR is required to ensure compliance with Stage IIIB/V emission standards. Further discussion with industry on the appropriate level of uptime (i.e. when the SCR is reducing NOx) and strategies for measuring downtime (i.e. when the SCR is not reducing NOx) is therefore recommended before developing standards. However, there is the potential for Great British Railways (GBR) to define common operating practices, including requiring that operators should

ensure that AdBlue tanks are filled up where practical. Other measures include recommending that the effective 'range' of AdBlue tanks be oversized compared to the fuel tank range. Best practice would then require that the AdBlue always be topped up during the time the vehicle is connected to the fuel pump and being refuelled.

- Audio data collection should be used for targeted assessments, including understanding the range of engine rpm in each notch while in torque convertor mode, real idle conditions, transitions between torque convertor and fluid coupling modes in DHMUs, and transitions between torque convertor to lowest gear and between gears in DMMUs. This data can be used to delineate future drive cycle weightings.

Abbreviations

AC	Alternating current
BEMU	Battery electric multiple unit
AR5	Fifth Assessment Report
CARB	California Air Resources Board
CEN	European Committee for Standardisation
CFR	Code of Federal Regulations
CH_4	Methane
CLEAR	Clean Air Research Programme
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CPC	Condensation particle counter
DC	Direct current
DEMU	Diesel electric multiple unit
DHMU	Diesel hydraulic multiple unit
DMMU	Diesel mechanical multiple unit
DMU	Diesel multiple unit
DOC	Diesel Oxidation Catalyst
DPF	Diesel particulate filter
ECU	Engine control unit
EGR	Exhaust gas recirculation
EPA	Environmental Protection Agency
ETS	Electric train supply
FID	Flame ionisation detector
GBR	Great British Railways
GWR	Great Western Railway
GWP	Global warming potential
HC	Hydrocarbons
HVO	Hydrotreated vegetable oil
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
ISO	International Standards Organisation
LNG	Liquid natural gas
NDIR	Non-dispersive infrared
NO	Nitric oxide

NOx	Nitrogen oxides
NO_2	Nitrogen dioxide
N_2O	Nitrous oxide
NESHAP	National Emission Standards for Hazardous Air Pollutants
NRMM	Non-road mobile machinery
OTMR	On-train monitoring recorder
PEMS	Portable emissions measurement systems
PM	Particulate matter
$PM_{2.5}$	Particulate matter less than 2.5 micrometres in diameter
PM_{10}	Particulate matter less than 10 micrometres in diameter
PN	Particle Number
RH	Relative humidity
RICE	Reciprocating internal combustion engines
SCR	Selective catalytic reduction
SO_2	Sulphur dioxide
TPE	TransPennine Express
THC	Total hydrocarbon
UNECE	United Nations Economic Commission for Europe
UV	Ultraviolet
WHSC	World Harmonised Stationary Cycle
WHTC	World Harmonised Transient Cycle

Contents

1 Introduction

1.1 Context

The GB Rail Industry Air Quality Strategic Framework, which was published in June 2020, details a series of recommendations to achieving air quality improvements in the rail sector through monitoring, modelling, and mitigation[1]. One of these recommendations is to:

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

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

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

It is important to note that the focus of this project is on understanding and assessing the effectiveness of emissions mitigation solutions for rail: it does not address intermodal comparisons although it does provide the basis for ensuring real-world rail emissions can be calculated accurately on a transparent basis.

1.2 Project scope

The primary scope of this project was the development of an emissions Testing Protocol which provides a repeatable representation of the common duty cycles for each major rolling stock class that has the potential for emissions mitigation retrofit solutions. The Testing protocol will provide a cost effective, practical and straight forward method to

[1] GB Rail Industry (2020). *Air Quality Strategic Framework*. RSSB

benchmark the performance of retrofit mitigation options across diesel rolling stock types. Through taking a detailed granular approach to defining required mode test points and then realistically weighting emissions results for these mode test points across the drive cycle – for before and after an emissions mitigation option is implemented – the Testing Protocol can be used to assess the emissions performance of all current retrofit mitigation options that are realistic and feasible for use in GB rail. Existing retrofit schemes are largely based on engine or abatement changes. The Testing Protocol proposed for UK rail in this project takes into consideration the current technological landscape, including newer technology such as hybrid-battery options. Data has been compiled for the operating conditions that these various mitigation options might encounter amongst relevant rolling stock classes and journey types and has been used to define appropriate mode test points.

A suitable reporting format for the emissions testing data and relevant additional parameters has also been developed, along with recommendations on the type of testing facilities and equipment required depending on the rolling stock type and type of testing being carried out. Consistent and complete reporting of emission testing results will enable learnings to be transferred to other rolling stock types and mitigation solutions. Consideration has been given to the technical requirements to monitor and ensure ongoing 'through-life' emissions performance of retrofit systems.

The Testing Protocol developed in this project can be easily adapted to undertake through-life testing of rail diesel engines and relate the emissions measurements back to original certification or "as new" levels. Such through-life testing can be used to identify engines where emissions increase significantly with age and mileage. Appropriate testing frequencies and a sampling methodology have been established.

Appropriate emission reduction targets for the main air pollutants of concern in the rail sector (nitrogen oxides, NOx; nitrogen dioxide, NO_2, particulate matter less than 10 micrometres in diameter, PM_{10}; and particulate matter less than 2.5 micrometres in diameter, $PM_{2.5}$) have also been considered in relation to different emission mitigation solutions. Such targets are intended to be challenging but not overly restrictive, and they will vary depending on whether applied to the overall drive cycle, to stationary idling, or to periods experienced by passengers while onboard services. Case studies have been developed that show how targets can be applied for different mitigation solutions and in different situations.

1.3 Purpose of this report

This report presents the background, underlying data, and core approach to the development of the Testing Protocol which is a separate document[2]. It is aimed at senior industry stakeholders and technical specialists to help them understand the methodology behind the development of the Testing Protocol. This Methodology Report is intended to provide an explanation of the purposes of the Testing Protocol, and how it can be widely applied to ensure effective and transparent benchmarking of emissions mitigation solutions for rail. It should aid the development of robust business cases for investment, as well as supporting the development of knowledge and capacity, both within the rail industry and amongst emission testing specialists, of the issues and challenges that are unique to measuring and reducing emissions of air quality pollutants on the GB rail network.

1.4 Report Structure

The core approach to this project, of making measurements at mode test points reflective of real-world usage that can then be aggregated to evaluate emissions for total drive cycles or specific situations, is discussed in Section 2. Background material and key concepts on emissions measurement are provided in Section 3. Key features and learnings from existing emission standards and approval schemes for rail and other sectors (discussed in more detail in the associated Literature Review Report[3]) that informed the development of the Testing Protocol are given in Section 4. Section 5 presents rolling stock specific aspects of the Testing Protocol, including important differences for available testing options between diesel-electric, diesel-hydraulic and diesel-mechanical transmissions. The compilation of relevant data by rolling stock class is described in Section 6. Required facilities, capabilities and equipment are reviewed in Section 7, while considerations for setting emission reduction targets are discussed in Section 8. Adaptation of the Testing Protocol to different circumstances is covered in Section 9 and issues relating to conducting through-life testing are discussed in Section 10. Conclusions and recommendations are provided in Section 11.

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[2] Grennan-Heaven, N., M. Gibbs and L. Gleeson (2022). CLEAR: Performance requirements and testing protocols for emissions mitigations – Testing Protocol. RSSB.

[3] Grennan-Heaven, N., L. Gleeson and M. Gibbs (2022). CLEAR: Performance requirements and testing protocols for emissions mitigations – Review of emissions mitigation measures and retrofit approval schemes. RSSB.

2 Project approach

This section describes the key requirements for the Testing Protocol that have then dictated the approach used in developing the Testing Protocol.

2.1 Key requirements

The Testing Protocol must be flexible and be able to deal with the full range of potential mitigation solutions applicable to GB rail. This means dealing with the whole system that can affect emissions and being able to look beyond just engine testing. Regulatory engine testing is based on a fixed pre-defined drive cycle (i.e. the total proportions of time spent in particular engine modes) and focuses on a single metric (typically in g/kWh) across the complete drive cycle. However, this approach may mean that issues at particular points of the drive cycle, such as idle, may not be addressed. It also does not reward solutions, such as battery hybrid rafts, that involve not running the rolling stock engines in key areas such as enclosed terminus stations.

A focus on emissions across the complete drive cycle needs to be complemented by the ability to consider emissions in particular locations on the GB rail network. Recently, attention on customer and staff exposure to air quality pollutants at specific locations on the GB rail network has increased, including at stations and depots, and onboard passenger trains[4, 5, 6]. In these locations the duty cycle (the specific times spent in each engine mode) will differ from the overall drive cycle for any type of rolling stock. For instance, duty cycles in stations and depots will be dominated by idling while stationary, while duty cycles during passenger service will be dominated by full engine power, idling while coasting and braking, and some idling in stations.

Understanding the emissions specific to different situations is crucial to make decisions on the most successful mitigation options. For example, a measure may reduce total emissions but may have the greatest impact at reducing emissions during long stretches of travelling through open countryside and not when the train is stationary and idling in a station.

The Testing Protocol will need to enable effective evaluation of the impact of mitigation solutions in key situations such as stations/depots and onboard, and to reflect the duty cycle in these situations, where the proportions of different engine modes will differ from the total drive cycle. A granular understanding from testing will be necessary to evaluate measures that will be specific to, and have an effective impact in, these

[4] 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

[5] 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.

[6] Green, D., A. Font, A. Tremper, M. Hedges, S. Lim and B. Bos (2021). CLEAR: Analysis of Air Quality On Board Trains. RSSB.

situations. Granularity in the Testing Protocol is therefore crucial to accurately measure emissions, with a single metric representing the whole drive cycle being of limited utility.

Onboard emission testing with the train moving (mirroring dynamic road emission testing with vehicles in motion) has proved to be impractical on current rolling stock. Such dynamic testing may also only be directly applicable to the routes and service patterns that the testing takes place on, with substantial work both at the time of testing and later needed to make it transferrable to other routes and service patterns. Furthermore, the original testing may not contain data relevant to the circumstances that occur on other routes and service patterns.

2.2 A granular approach

The chosen approach for the Testing Protocol will ensure maximum flexibility and transferability of the testing data. This is achieved through gathering sufficient (but not unduly onerous) emissions testing data from static engine emissions testing at defined mode test points. This data is then combined with data on engine operating conditions encountered during real running.

By conducting and fully documenting testing at mode test points reflective of real-world usage for individual rolling stock classes (and different combinations of engine and transmission if applicable) the resulting data can be aggregated using different weightings for different duty and drive cycles to derive (model) total emissions, for either before or after the implementation of an emissions mitigation solution. The data can be analysed in multiple ways to understand the impact of potential emissions reductions in different situations, while enabling transparency and transferability. While it is important to understand the total emissions of the rolling stock both before and after mitigation options are installed, it is also important to understand how the emissions can be reduced by varying degrees throughout the drive cycle of an engine.

The Testing Protocol requires the testing and reporting of individual mode test points, i.e. at a more granular level than that required for regulatory emissions approvals. This will enable a better understanding of potential emission reductions in particular locations which are of current concern for air quality (for instance idling in enclosed stations). It will also enable the testing results and learnings to be used for other purposes, thus offering more value to the industry.

Due to the differences in design and usage between road and rail vehicles, the number of individual mode test points needed for realistic rail vehicle emission testing is far smaller than the equivalent number needed for dynamic test cycles in road emission testing. This is especially the case for locomotives. The engine operating conditions are also far more fixed and predictable than for road vehicles and, therefore, those operating conditions are generally maintained for longer periods of time and are more stable. As a result, the emissions are also more stable.

2.3 Addressing transient scenarios

Fixed mode test points for regulatory testing, typically with defined rpm and power settings, are where average emissions are determined once the engine is stabilised at that particular mode. However, gathering useful understanding in some circumstances cannot be done with test mode points alone. In these cases, specific test scenarios are required where the evolution in emissions over time in response to dynamic condition is recorded and reported (rather than just reporting average values). For instance, this may be required when evaluating the effects of cold starts or fall-off in selective catalytic reduction (SCR) effectiveness as exhaust temperature declines. Such scenarios require that a specific path (a temporal sequence) through certain defined test points must be executed for a given duration of time.

Collecting and reporting testing data at multiple mode test points not only helps address testing a specific solution but, in many cases, offers transferability to address other solutions. This applies in the majority of cases. However, in a few situations, such as evaluating SCR performance in certain locations, it will be necessary to carry out specific testing scenarios where defined test points must be tested in a particular sequence.

Where aggregated emissions for all or particular parts of the drive cycle are required, time-based weighting maths should be used rather than power-based weighting maths. The latter can obscure the impact of idling emissions in key locations on the GB rail network such as stations and depots.

In addition, testing should cover cold, warm, and hot starts. Mitigation options such as stop-start and increasing engine shutdown are better than running in idle for emissions, but the minimum sensible shut down period must be established to ensure that the energy cost is taken into consideration. Another important consideration is the temperature dependence of SCR systems, and how to test for this. The Testing Protocol should therefore recommend measurement of exhaust temperatures and emissions over time after transition from full or half load to idle.

2.4 Addressing post installation changes to mode test points and drive cycle

For some mitigation options, for example changing fuel injectors, there will be no before and after change in both mode test points and the drive cycle. However, many solutions will result in changes to the mode test points and/or drive cycle after the solution has been implemented, making comparisons of emissions more complex. The Testing Protocol will need to ensure that sufficient data is collected to fully assess emissions before and after a mitigation measure has been implemented, and it will therefore need to be able to handle resultant changes to the mode test points and/or drive cycle.

For DMUs, having granular-level testing data by multiple mode test points per engine power notch (hereafter referred to as notch), when combined with an understanding of how the drive cycle will change, allows accurate modelling of the expected future operating conditions and hence emissions. In such a manner the impact on emissions (as a total and for certain situations), before and after implementation, can be more deeply understood. This is particularly necessary where there are multiple changes, for instance to both the mode test points and the drive cycle.

Diesel hydraulic multiple unit (DHMU) and diesel mechanical multiple unit (DMMU) drive cycles have significant variations due to route geography and stopping patterns. These are more variable compared to diesel electric multiple unit (DEMU) drive cycles. In addition, units that are less optimised for particular routes will have higher fuel consumption and emissions; such variations between rolling stock type and engine type can be as high as 30%. For instance, the Class 159 stopping patterns and duty cycles are very different west and east of Salisbury. There is therefore the potential to identify which rolling stock are optimal from an emissions point of view for particular route/service patterns. The Testing Protocol is adaptable to such different circumstances.

2.5 Key benefits

The Testing Protocol will keep test points and weightings separate to allow flexibility as solutions and measures to reduce emissions evolve. By collecting and retaining the data at a granular level it can be "cut many ways" as part of detailed analyses of particular solutions. In addition, retention of this detailed data can enable later comparisons between modelled outcomes of mitigation options applied to different types of rolling stock, service patterns or locations.

The effects of engine-off solutions can be covered by the Testing Protocol. Existing engine testing standards focus on engines in isolation, but most diesel multiple units (DMUs) have several engines on one train. The whole rolling stock must be considered to effectively evaluate the total emissions impact of turning off one or more of these engines during key points of the DMU's drive cycle. This is enabled by emissions testing at the relevant mode test points then combing these results with the future changed weightings for the new drive cycle of the engines which remain on and provide power.

2.6 Applicable rolling stock

The Testing Protocol is primarily aimed at older rolling stock where engines tend to have the highest emissions and are often not subject to any emission standards. For such rolling stock there is thus a high potential for retrofit mitigation solutions to make a substantial impact on emissions. The rolling stock classes (or families where key characteristics are similar) that are covered in the Testing Protocol are:

- Class 150, 153, 155, 156
- Class 158, 159
- Class 165, 166

- Class 168, 170, 171
- Class 172
- Class 175
- Class 180
- Class 185
- Class 220, 221, 222
- Class 66
- Class 68
- Class 70.

Different rolling stock will have different requirements and engine structure, and therefore the Testing Protocol must be able to adapt to different classes, ensuring that the significance of emissions and potential emissions reduction can be gauged. For this reason, mode test points and weightings are specified for each train class or family, engine and vehicle maximum speed.

An example is Class 158 and Class 159 trains, both of which have three different engines fitted to them with three different engine maximum speeds and peak torque speeds. In some cases, these engines also have different gear box set-ups. Therefore, the engines will need different test points, resulting in a more detailed testing schedule.

3 Background and key concepts

3.1 Key concepts of emissions measurement

The main emissions from engines are generated during the combustion of fuel and engine oil. These include carbon dioxide (CO_2), carbon monoxide (CO), HC (hydrocarbons) and sulphur dioxide (SO_2). In addition, particulate matter (PM) is also emitted in engine exhaust. NOx is formed from nitrogen and oxygen in the air due to the high in-cylinder temperature and pressure.

3.1.1 Measurement of gaseous emissions

Gaseous emissions measuring equipment measures the concentration of gases in the exhaust flow from the engine. This is typically measured as either a percentage for higher concentration gases (e.g. oxygen and carbon dioxide) or parts per million (ppm) for lower concentration gases (e.g. nitrogen oxides, carbon monoxide etc.). However, to understand emissions the quantity or normalised quantity of emissions per unit of activity needs to be ascertained, not just the concentration. This needs additional data to be collected alongside the emissions concentration measurement. Three core normalised metrics are widely used to quantify emissions:

- emissions mass per unit energy produced (g/kWh)
- emissions mass per unit exhaust gas volume (g/m^3)
- emissions mass per unit time (g/s).

Gaseous emissions are usually measured on a second-by-second basis and the results used to calculate an average emission level for a particular engine operating mode.

3.1.2 Measurement of particulate matter emissions

Particulate matter (PM) comprises solid and/or liquid material ranging from a few nanometres in diameter (about the size of a virus) to around 100 micrometres (100 µm, about the thickness of hair). The impacts of PM range from health effects arising from direct inhalation, to impacts on climate and precipitation. In general, the smaller and lighter a particle is, the longer it will stay in the air. Larger particles (i.e. greater than 10 µm in diameter) tend to settle on the ground in a matter of hours, whereas the smallest particles (i.e. less than 1 µm) can stay in the atmosphere for weeks and are mostly removed by precipitation.

Two sizes of particulate matter are commonly referred to:

- PM_{10} – medium-sized 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} emissions are measured (as this is the regulated metric) so all references to PM in this report are to PM_{10} unless otherwise stated. However, smaller particulates, i.e. $PM_{2.5}$, are of greater concern for health reasons. As there is limited data for the ratio of $PM_{2.5}$: PM_{10} emissions in engines in rail use, it may well be more useful, where possible, to also measure $PM_{2.5}$ as it is more relevant to understanding health-specific rail air quality issues. The ratio of $PM_{2.5}$: PM_{10} will vary with engine power settings conditions, hence in some cases a detailed comparison of $PM_{2.5}$ and PM_{10} would be very useful for overall rail exhaust emissions understanding.

In more recent engine emission standards (between 2015 and 2020) an additional particulate measurement concept, the Particle Number (PN), has been introduced. The PN is a measure of the total number of particles and, combined with mass-based PM measurements, gives an idea of the distribution of particle sizes.

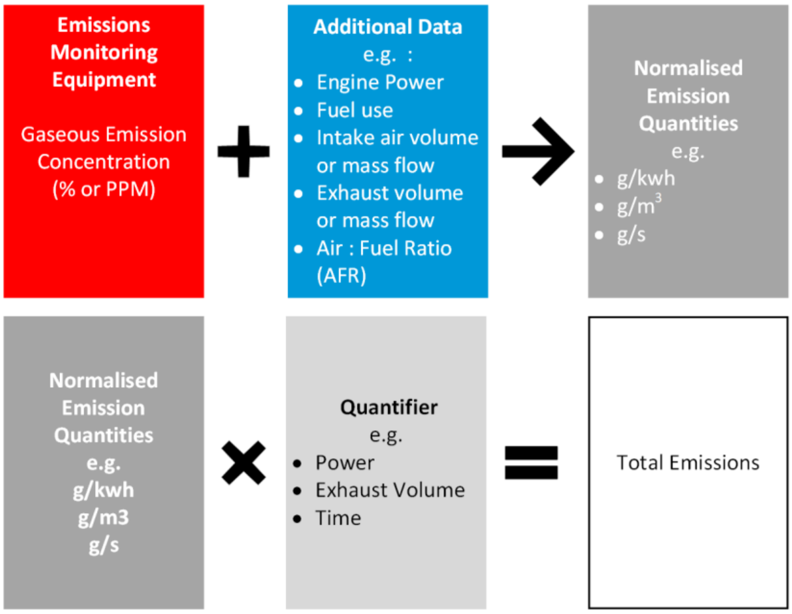
Particulate measurements are more technically challenging and have traditionally been measured differently from gaseous emissions. Emissions can be measured using a gravimetric method where the total mass of particulates captured by a filter (weighed before and after the test) is recorded. Traditionally, the PM was measured for the whole drive cycle and not for individual engine operating modes. Improved emission measurement studies do measure PM during all steady state modes within the test cycles. More recently, emission standards in Europe, the US and other regions have included more complex transient drive cycles. These emissions standards have also required the development of second-by-second PM measurement techniques in parallel with the traditional complete test filter measurement for calibration purposes. These standards also require the measurement of PN. This means that it is now far easier to collect PM data for each engine operating mode. However, each equipment manufacturer has typically adopted a different measurement technique. Currently, there is also less of this new equipment available compared to gaseous measurement equipment, although this situation should improve over time.

Since PM has traditionally been harder to measure than gaseous emissions, just one normalised metric is widely used to quantify emissions, namely, emissions mass per unit energy produced (g/kWh). For PN, the normalised metric is the number of particles per unit energy produced (PN/kWh).

3.1.3 Measurement of additional operational data

As well as measuring the quantity of gaseous emissions or PM, additional data needs to be collected including engine power, fuel use and exhaust gas volume or mass to be able to produce normalised metrics.

Figure 1 Emissions data collection and output formats



3.2 Relevant available and potential mitigation options

The Testing Protocol must be able to address all of the following emissions mitigation options which could potentially provide real-world emissions reductions for GB rail:

- Best available crankcase breather filtration
- Selective catalytic reduction (SCR)
- Diesel Oxidation Catalyst (DOC)
- Diesel particulate filter (DPF)
- Exhaust gas recirculation (EGR)
- Timing retardation
- High pressure fuel injection
- Engine remap
- DMU battery hybrid – mechanical or electrical transmission
- High functionality shore supplies
- Improved turbocharger
- Charge air cooling
- New engine (compliant with current regulations)
- Alter transmission fixed gearing ratio
- Selective engine shutdown (DMU)
- Bi-mode propulsion
- Battery electric multiple unit (BEMU)
- New traction electrical equipment
- Electric-powered compressors and battery upgrades
- Alternative fuels: hydrogen, liquid natural gas (LNG)/compressed natural gas (CNG), hydrotreated vegetable oil (HVO), Fischer-Tropsch process drop-

in diesel substitutes fuels, emulsified diesel

These options were evaluated for:

- their impact on NOx, PM and CO_2 emissions
- their impact on fuel consumption
- the typically fitted compliant engines
- the indicative cost per DMU car or locomotive.

Further details are provided in the associated Literature Review report[7].

Parts, and designs, must be carefully specified to ensure what is tested is what is supplied. This issue is far more critical for some technologies than others, being particularly pressing for battery capacity, battery charge rates and SCR catalyst temperature. Here, the risk of substitution could substantially impact emissions performance. This focus will help to reduce the likelihood of there being an emissions reduction efficiency gap between the real-world use of a part and the results produced during testing. Furthermore, the performance of some technologies degrades over time (e.g. catalysts and batteries). Hence, as discussed in Section 10 of the Testing Protocol, for certain measures additional data items should be recorded to ensure that expected performance of these measures can be checked in the future.

3.3 Regulatory versus real-world drive cycles

Regulatory emissions testing aims to produce comparable testing under identical standardised conditions. However, this approach is often not always useful for understanding real world emissions.

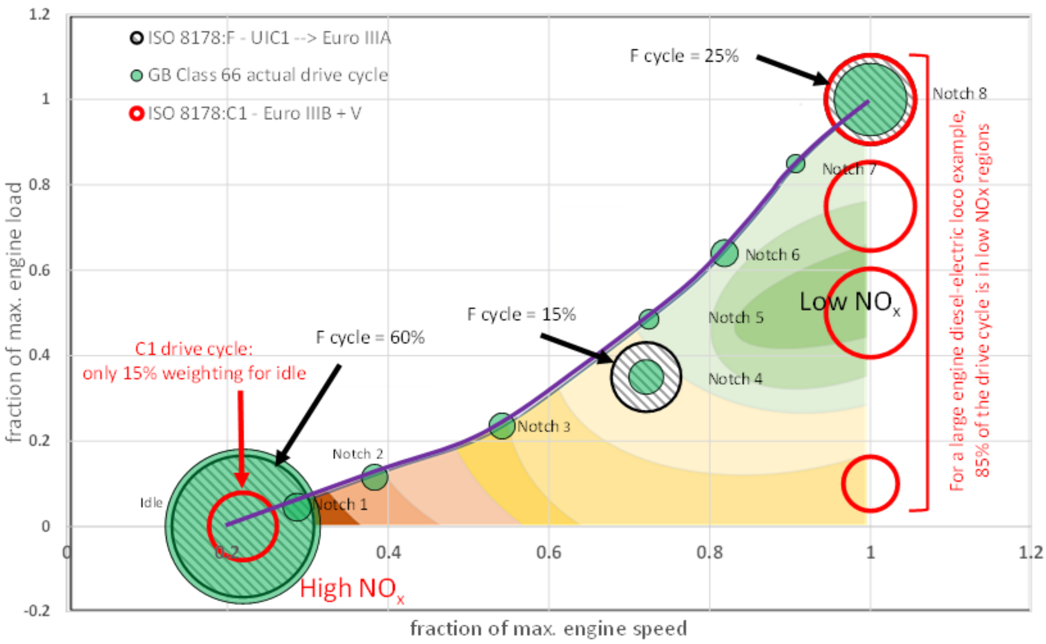
For example, virtually all global regulatory non-road mobile machinery (NRMM) engine testing standards state that measuring emissions at idle should be with minimal auxiliary loads on a potentially partly stripped-down engine. This enables the results to be more standardised, aiding comparability. However, the real engine running conditions and idle settings for an engine when installed on a rail vehicle will be very different to those used during regulatory testing. Depending on which particular rolling stock type, real engine idle loads are 4 to 10 times higher in real use than those measured in regulatory test scenarios[8]. Additionally, real idle engine conditions generally tend to share the ultra-lean combustion and high air-to-fuel ratio of the characteristics of no-load idle than that of low engine power settings.

[7] Grennan-Heaven, N., L. Gleeson and M. Gibbs (2022). *CLEAR: Performance requirements and testing protocols for emissions mitigations – Review of emissions mitigation measures and retrofit approval schemes*. RSSB.

[8] Grennan-Heaven, N. and M. Gibbs (2020). *CLEAR: Fleet-wide assessment of rail emissions factors*. RSSB

The International Standards Organisation (ISO) 8178 F drive cycle, applicable to the Euro IIIA and earlier standards for locomotives, is close to the actual drive cycle for the Class 66 locomotive (Figure 2). However, the ISO 8178 C1 drive cycle, which is currently applicable to railcars (DMUs) and locomotives, contains a very limited proportion of time in idle. All rail rolling stock spends a high proportion of time in idle, and therefore the C1 drive cycle is not representative of real-world usage.

Figure 2 Comparison of regulatory drive cycles, the real GB freight drive cycle and indicative regions of idealised NOx emission



Rather than focusing on regulatory emissions testing, it is far more useful for the GB rail industry's understanding of emissions to focus on real-world engine settings, conditions and emissions, while maintaining as much comparability between studies as possible. Comparability is important: it allows operators and stakeholders to understand the current baseline and to meaningfully evaluate emission reduction solutions. It also enables leveraging of test results for other situations where emission factors by notch and on-train monitoring recorder (OTMR) data can be used to understand trip emissions for different train loadings or other train classes with similar engines[9].

[9] Grennan-Heaven, N. and M. Gibbs (2020). *CLEAR: Fleet-wide assessment of rail emissions factors*. RSSB

3.4 Mirroring testing approaches from other sectors

In the road sector, there are two main testing and drive cycle weighting approaches currently used:

- Stationary cycles e.g. the World Harmonised Stationary Cycle (WHSC) and the older European R49 and US 13-point test cycles it was based on. Here the steady state emission averages for sampling periods of several minutes at each of a small number of mode test point are utilised, with weights applied afterwards. At least 20 seconds is allowed for transient conditions during transition at the start of each mode test point for conditions to stabilise. (For NRMM, ISO 8178:C1 is very similar to the older European and US cycles.)
- Transient cycles e.g. the World Harmonised Transient Cycle (WHTC) which has a far higher number of mode test points following a detailed script but the time at those mode test points can be just a few seconds, with results more variable than for testing with the stationary cycles. Hence this approach requires more repetition to ensure results are valid and consistent.

In the rail sector, potentially far fewer fixed test points are required than in the road sector. The number of test points can be around 250 in the road transient cycles test cycle compared to potentially a maximum of around half that for a DHMU or DMMU engine or as few as 10 for locomotives. In rail, more time is spent operating in each mode: for example, when emissions testing locomotives, engines will spend around ten minutes at each mode test point. This allows for repeatability to be achieved during the longer time period at each test point, yielding greater accuracy than for road.

The approach we have taken in the protocol is to follow the stationary cycle approach, with locomotives / DEMUs having a similar number of mode test points to road but with a greater number of mode test points for DMU engines than is traditionally used in the road sector but comparatively fewer than used in the equivalent road transient cycles. The dynamic scenarios for understanding the impact of transient effects mirror parts of the road transient cycle approach. Using similar testing approaches to those already used in other sectors helps those from the engine testing sector as they will already be familiar with the concepts and will have done similar testing before.

3.5 Understanding real idle conditions

In current regulatory testing, it is assumed that idle conditions include a small amount of power. However, depending on the particular rolling stock type, real engine idle loads are 4 to 10 times higher in real use than those measured for regulatory testing[10], and the engine conditions generally tend to share the ultra-lean combustion and high air-to-fuel ratio of the characteristics of idle than that of low engine power settings. For instance, the smallest average auxiliary load for a DMU engine is circa 20 kW for Classes 150-156,

[10] Grennan-Heaven, N. and M. Gibbs (2020). *CLEAR: Fleet-wide assessment of rail emissions factors*. RSSB.

while Classes 185 and Class 68 require loads of 100 kW per engine in idle, whereas idle in regulatory testing is 5 kW or less.

In January 2022, First Group, the parent company of TransPennine Express (TPE) and Great Western Railway (GWR), sought expressions of interest from suppliers for provision of fleet bi-mode locomotives for the TPE locomotive-hauled services and GWR sleeper services. The requirement clearly outlines the high electric train supply (ETS) or hotel load requirements of modern coaching stock:

> *"The MKVa rakes are nominally 5-car configuration, …, maximum ETS load of 300kW. The MkVa design also allows for an additional 2 x coaches to be homologated into the design, therefore, the locomotive should be able to operate with up to 7-cars … with ETS load to 410kW."*

This indicates a maximum ETS load of 60 kW per Mk 5A coach (with total potential auxiliary loads including non-electrical loads for equivalent DMU vehicles with similar features being higher still).

> *"An option must also be provided to supply up to a further 5 locomotives for the existing GWR riviera sleeper service operated by Mk3's (up to 9 coaches at approx. 344 tonnes tare mass and ETS draw at 340kw)."*

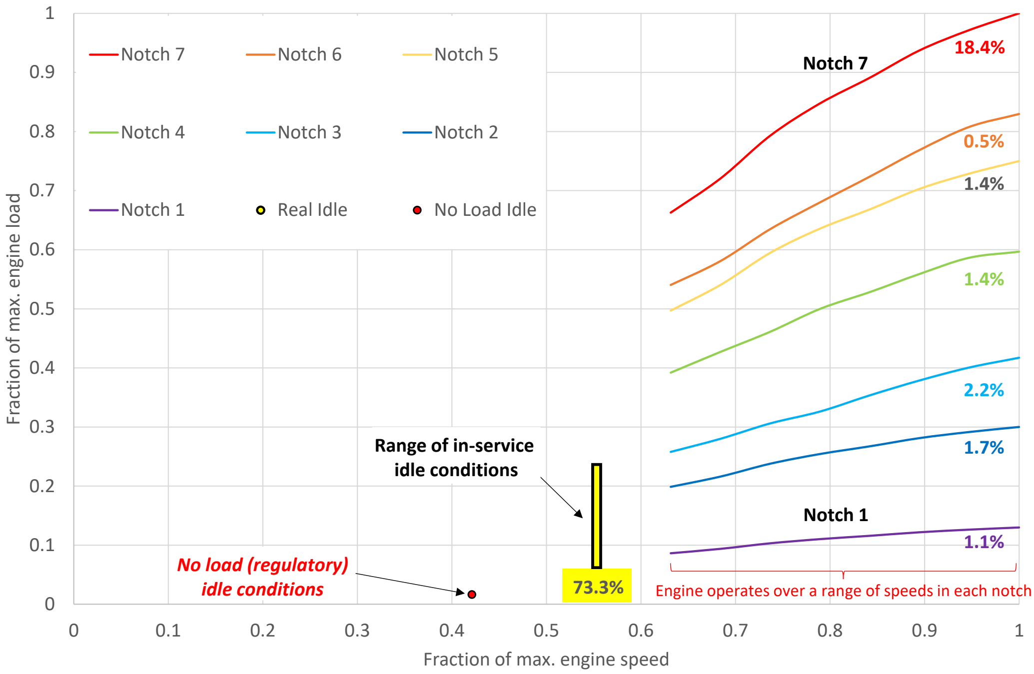
This indicates a maximum ETS load of 38 kW per Mark 3 sleeper coach. The maximum ETS load for Mark 3 and Mark 4 non-buffet coaches currently remaining in daytime use is 30 kW and for Mark 3 and Mark 4 buffet coaches is typically a maximum of 70 kW.

The auxiliary alternators on most modern DMU designs can supply 70 kVA, equivalent to supplying 60 kW of electrical equipment. For a small number of DMU vehicle designs, the maximum electrical load per vehicle is even higher still. For example, for vehicles where heating is provided exclusively from electric power without using waste heat from the engine, and for DMUs with larger engines that have greater cooling requirements.

Regulatory idle specifies a lower rpm and power than any of the real idle values listed above, which can impact the emissions associated with the idle engine condition. Figure 3 demonstrates the importance of considering real idle, which is usually a loaded condition.

Virtually all Notch 1-7 engine operation is above peak torque speed, which occurs at a fraction of maximum engine speed of approximately 0.65-0.7. The ISO 8178:C1 cycle regulatory mode test points (excluding idle) are concentrated on the maximum loaded engine speed and the engine's peak torque speed so some of the mode test points recommended here are identical or very close to the ISO 8178:C1 cycle regulatory mode test points (albeit with vastly different weightings). To ensure that real-world conditions will be included in testing, the Testing Protocol requires consideration of real idle, which is significantly different to regulatory idle conditions, unlike some of the Notch 1-7 mode test points.

Figure 3 Example for a Class 170 showing regulatory vs real world idle and relative time in notch over the total real world drive cycle



While the values discussed above are the maximum potential ETS loads (e.g. when maximum heating or cooling is required), the real ETS and total auxiliary load will vary and often be lower than these maximum loads. Hence, rather than using a single load condition for idle, it will be useful to define three separate levels of overall auxiliary loads for rolling stock. These defined auxiliary loads should be used in emission testing. This is especially the case at idle where the variation in auxiliary loads has a significant effect on the overall engine loads. The Testing Protocol therefore recommends using a range of three auxiliary idle loads:

- Minimum (typically lowest encountered loads e.g. when not running in service, most loads are zero or minimal e.g. HVAC is off, compressor is not running, low other electrical loads)
- Typical average (typically in-service loads, most loads are average e.g. HVAC is on with moderate heating or cooling requirements (spring/autumn), light compressor loads, moderate but not high other electrical loads)
- Maximum (high in-service loads, most loads are high e.g. HVAC is on with high heating or cooling requirements (winter /summer or soon after being turned on), high compressor loads, not high other electrical loads)

3.6 Meeting applicable emission standards

The primary purpose of the Testing Protocol is to ensure retrofitted mitigation measures will be effective in real-world conditions. Such measures can be expected to have the most impact on reducing emissions from older rolling stock with engines that are not subject to emissions standards. Furthermore, there is more freedom to develop and apply mitigation solutions to such rolling stock that will address emissions in real-world conditions since there is no requirement to ensure compliance with emission standards. Newer engines subject to Stage IIIA/IIIB/V standards would have to remain compliant with their applicable standard: any alterations or additions that reduce real world rail emissions would also need to maintain (or reduce) emissions under the regulatory testing requirements that they were originally certified to. This restriction may reduce the potential to deploy innovative solutions that would be effective at addressing specific air quality issues on the GB rail network.

It is important to note that, of the rolling stock classes in scope for the Testing Protocol (see Section 2.6), only Class 68 and 172 are subject to emission standards and therefore there is more freedom to consider effective mitigation options for all other classes.

4 Key features incorporated from existing emissions standards and approval schemes

As part of this project, a literature review[11] was made of existing schemes in the road, marine, construction, and NRMM sectors for the independent approval of emissions control systems for both new and retrofitted engines. Key features of these schemes, many of which come from the US EPA approach to rail emissions, have been incorporated in the Testing Protocol and are discussed in this section.

4.1 Recording test point data

The US EPA publishes notch-level emission testing data for all new and retrofitted rail engines, which must follow a standardised reporting format. This single repository enables an accurate granular understanding of how emission reductions meet evolving emission standards, and it represents a rich resource that benefits US rail industry stakeholders. Some of this information, and indeed the general approach, is directly transferable to the GB rail industry.

The Testing Protocol requires recording of the data in a standardised format that captures all relevant data fields. This will ensure transparency and transferability.

4.2 Drive cycle time weighting

European schemes, such as the United Nations Economic Commission for Europe (UNECE) R132 scheme for older NRMM engines, use drive cycle weighting maths defined by power in notch. The single metric emissions factor in these schemes is defined as:

$$g/kWh = \frac{total\ emissions\ during\ tests}{total\ energy\ during\ tests}$$

The drive cycles maths have, historically, been designed so that a single PM filter could be used for the entire test. This weighting focuses on emissions at high power outputs with the weighting effectively built into testing. As a result, emissions in idle at stations and other locations such as depots are not fully captured. (Typically 20-25% of total time in idle occurs while the train is coasting or braking and the majority while stationary.)

By contrast, US schemes and for Euro Road HD VI, time-based weightings are applied post testing such that:

$$g/kWh = \sum_{n} (emission\ factor\ mode\ n\ \times weighting\ mode\ n)$$

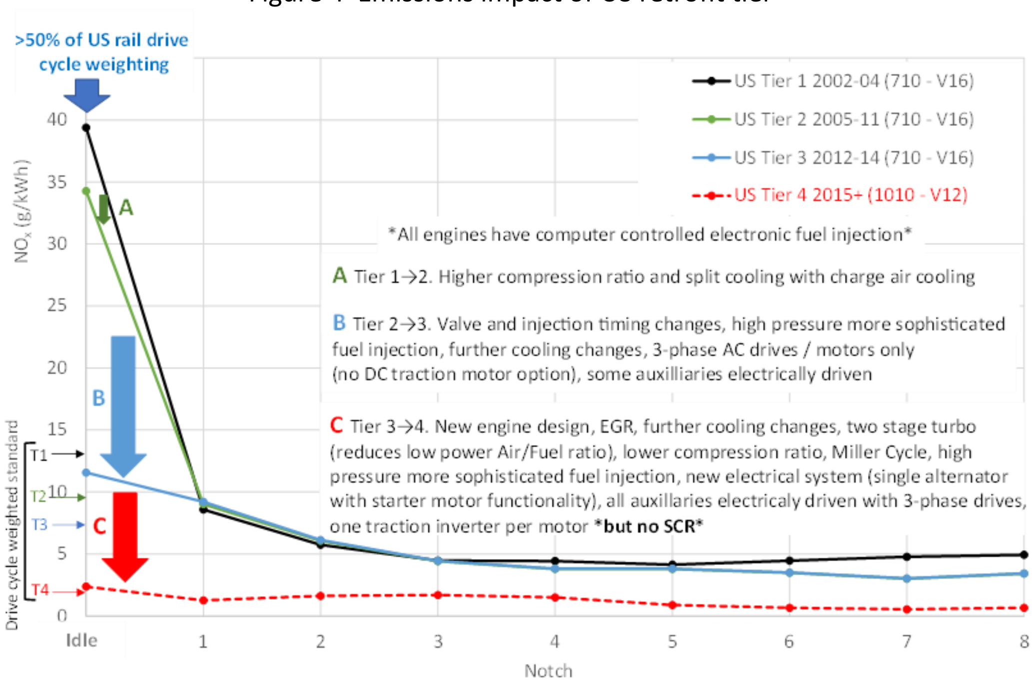
[11] Grennan-Heaven, N., L. Gleeson and M. Gibbs (2022). *CLEAR: Performance requirements and testing protocols for emissions mitigations – Review of emissions mitigation measures and retrofit approval schemes*. RSSB.

This emission weighting gives equal importance to each notch based on time specified in the drive cycle. As a result, a much greater focus is placed on addressing emissions at lower engine power in the US schemes.

To achieve a higher level of granularity and therefore accuracy in emissions testing, the US schemes use four separate regulatory drive cycles for rail. The US weightings can evolve over time to simulate changes in operation. For example, there is now significantly less idle in US rail due to the increased usage of stop-start technology and this has been reflected in a reduction in the proportion of idle in the regulatory drive cycles.

For all four US rail regulatory drive cycles, idle accounts for over 50% of the weighting. Therefore, the US rail industry is encouraged to reduce emissions at idle as a key way to achieve compliance. Figure 4 shows the measures taken to significantly reduce idle emissions across US locomotive fleets in response to this greater emphasis on idle.

Figure 4 Emissions impact of US retrofit tier



To measure a reduction in emissions as part of total use or specific situations, it is necessary to aggregate emissions from different mode test points and apply a weighting. The Testing Protocol requires flexibility in weightings and so needs a time-based approach, which focuses attention on the effectiveness of solutions in real circumstances.

4.3 Testing approach should be flexible

A success of the US EPA scheme was that it recognised that NRMM require adaptions to the approval scheme, where "one size does not fit all". The emission mitigation scheme for rail must therefore vary when needed, for example between train classes. A tailored approach must be taken whilst also aiming to minimise the number of variations to simplify the scheme as much as possible.

The US National Emission Standards for Hazardous Air Pollutants (NESHAP) for reciprocating internal combustion engines (RICE) focused on reasonably sized but easy reductions based on testing with a wide range of conditions and engines with mitigation solutions from both engine OEM and third-party suppliers. Importantly, it did not impose target percentages or other metrics that individual end users would have to meet. As a result, there were no testing requirements for the end users. Another important aspect of this scheme was its focus on the total real-world emissions over the entire engine life, rather than simply assessing initial reductions.

The Testing Protocol developed in this project, through requiring collection of mode test point data, provides building blocks to handle a wide range of mitigation solutions.

4.4 Defining the pollutants to be measured

US emissions regulations were changed in 2021 to require measurement and reporting of more pollutants (including methane and nitrous oxide which have a high global warming potential; GWP) during rail engine testing. However, no new non-road standards for these pollutants were proposed at this stage. Data on these pollutants will be collected to support potential future regulation in non-road (including rail) engine use.

Current road emissions regulation in Europe focus on reducing NOx and PM up to and including EURO VI, whilst also tackling some other pollutants such as unburnt hydrocarbons. However, looking towards the new EURO VII standards, the focus has shifted towards reducing emissions in urban areas rather than in the countryside and assessing Individual nitrogen oxides (i.e. NO, NO_2 and N_2O) separately rather than just NO and NO_2 combined as NOx. In addition, the assessment periods for testing will be extended to identify emission durability. This will be on par with engine life/rebuild intervals. As part of this new regulation, the intention is to reduce a variety of other emissions including of both air quality pollutants and greenhouse gases, such as finer PM, methane, nitrous oxide, and a more stringent focus on unburnt hydrocarbons and CO_2 efficiency. To achieve this aim, the future regulations will most likely increase the promotion of stop-start technology and "mild" hybrid technology in cars (i.e. where most of the energy savings are achieved through stationary or low-speed engine shutdown).

Measurement of additional pollutants, beyond the core air quality pollutants of NOx and PM, is included in the Testing Protocol. Emissions testing for air quality pollutants and global warming pollutants should require the following to be measured as a minimum:

- Gases:
  - Nitrogen oxides – NOx (total of both nitric oxide (NO) and nitrogen dioxide (NO_2), and which is the main rail air quality issue)
  - Carbon monoxide – CO
  - Total unburnt gaseous hydrocarbons – THC
  - Nitrous oxide (N_2O) emissions, which are not an air quality issue but a climate change one since nitrous oxide has a high GWP of 298 times that of CO_2 over a 100-year time period (Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5)[12], the current internationally agreed best understanding)
  - Methane (CH_4) emissions from liquid and compressed natural gas (LNG/CNG) powered engines, which are also not an air quality issue but a climate change one since methane has a GWP of 28 times that of CO_2 over a 100-year time period (IPCC AR5).
- Particulates:
  - Particulate mass – PM. While PM_{10} is the regulated PM emission metric, there is considerable benefit to also measuring $PM_{2.5}$
  - Particulate number – PN.

Although not air quality pollutants, the following gases also need to be measured for the calculation (post-processing) of final test results:

- Carbon dioxide – CO_2
- Residual oxygen – O_2 (the oxygen left in the exhaust stream that has not reacted to form CO_2, CO, NOx or SO_2).

4.5 Through-Life Testing

Another lesson to be learned from the US EPA schemes are their heightened focus on emissions durability when compared to European schemes. In the US, the total real-world emissions are assessed over the entire engine life since emissions durability has a large but mostly hidden impact on real world emissions through the lifetime of the engine. While reductions in emissions over time in US certification requirements appear smaller when compared to Europe, the real-world impact is greater and much more closely aligned to the reduction in certification levels.

[12] https://www.ipcc.ch/report/ar5/syr/

The emissions from an engine increase through its working life from its new or just-overhauled condition in a non-linear way. There will be very limited initial increases in emissions early in an engine's working life, but comparatively larger increases in emissions later in the engine's working life. This will have a substantial effect on the rolling stock's emissions and needs to be considered to accurately understand the complete emissions picture at different locations since emissions will vary between different trains depending on the amount of time since engine installation or overhaul. The Testing Protocol provides direction on how to gather this data. Extensive R&D programmes and modelling in the 1990s in the US has shown that through-life testing is crucially important for ensuring fleet-wide emissions reductions, for example US EPA-certified retrofit kits have to guarantee that there is no degradation in emissions for the first 30% of the engine's regulatory working life (roughly equivalent to 2.5 to 3.5 years typical locomotive use in the US).

While new engine testing in Europe theoretically includes the requirement for testing after 10,000 hours of running to assess degradation in emissions performance, it is extremely common to use an alternative permitted approach that involves testing once at only 1,000 hours. The emissions degradation at 10,000 hours is then estimated by considering a suitable similar proxy engine that has been tested at both 1,000 and 10,000 hours. This alternative approach exists due to the huge costs, especially for larger engines, that are associated with running 10,000-hour tests on dynamometers. The US rail emission testing uses a different approach: emissions testing is carried out for only a small number of engines (either 1 in 125 or 1 in 250 engines of a particular type, always with the same "reference" engines and locomotives being monitored) that are in service with the largest operators. As locomotive engine testing is conducted without removing the engine, the effort involved in testing is minimised compared to potential DHMU/DMMU engine testing. For US rail, through-life testing starts at 50% of the "working life" on the selected reference engines with testing just before and after the mid-working life scheduled fuel injector replacement then 75% of working life and immediately before major engine rebuild at the end of working life, at which point the engine working life begins again after testing post rebuild. At this point, the locomotive is already present at an overhaul facility with emission testing equipment. In the US all of the seven largest Class 1 operators are required to have emission testing equipment at a minimum of one of their overhaul facilities and several operators (Burlington Northern & Santa Fe, Norfolk Southern and Union Pacific) have more than one facility so equipped. The US through-life testing requirements are designed to have minimal impact on the operators, apart from the locomotive being out of service for slightly longer at intermediate or major overhauls, as well as fuel and personnel cost. The test cycle used is the same as the manufacturer's recommended test cycle used to test whether locomotive engines are performing in line with specification post overhaul. Hence, for the post overhaul emissions testing, the fuel cost of testing is already assumed in the cost of an overhaul.

In contrast, under the current European rail engine testing regime, engines are tested at a maximum of 40-50% of the working life between overhauls if 10,000-hour testing is conducted, else at just circa 5% of the working life when the 1,000-hour approach is used with the use of emissions degradation understanding from a suitable proxy. The success of the US scheme in generating the data with minimal locomotive down time especially around other required maintenance work has therefore informed development of the Testing Protocol.

5 Rolling stock specific aspects

Diesel-electric transmission and diesel-hydraulic/mechanical transmission rolling stock require different testing procedures. The former (especially locomotives) can be subjected to testing loads when connected to a resistive load bank while the engine is installed on the rolling stock, whereas the latter usually cannot, so necessitating the removal of the engine for testing. For electric transmission multiple units (Classes 220, 221, 222 and Hitachi's AT300 family of units (Class 800, 802, 805, 810) the engines, or complete engine rafts, are removed from the rolling stock for servicing which presents a potential opportunity for testing to use either approach on those vehicles.

Testing real idle emissions with the engine supplying realistic auxiliary loads (or equivalent loads if the engine is removed from rolling stock for testing) is especially relevant for understanding air quality issues in rail locations such as stations and depots and is much more useful than testing regulatory "idle" emissions. The Testing Protocol defines suitable average auxiliary loads to be used for the rolling stock covered by the Testing Protocol.

A potential alternative for real idle testing for DMU engines on dynamometers (that is applicable to all rolling stock types) is stationary idle testing on vehicle. This is very simple for all locomotives/DMU transmission types as the range of real engine loads at "idle" as installed includes supplying the non-traction loads of the rolling stock and is all that is needed for meaningful of analysis of real idle emissions and these loads can be controlled for testing to provide minimum, typical average and maximum loads as outlined in section 3.5.

In this section the simpler electric transmission cases (locomotive and DEMU) are covered first. The more complex hydraulic and mechanical transmission case are covered second and third, building upon the simpler electric transmission cases.

5.1 Engine testing configuration options

Given the restricted structure loading gauge on the GB rail network and potential safety issues arising from modified fuel and electrical systems when rolling stock is in motion, only stationary testing is practical. Table 1 shows the four real operating condition testing options for different engine transmission types and the requirements to derive the real operating condition loads for testing.

Table 1 Potential rail engine emissions testing set up options for different load conditions

	Electric transmission		Hydraulic or Mechanical transmission	
	All power settings	Stationary Idle only	All power settings	Stationary Idle only
Testing conducted "**On**" or "Off" Rolling Stock":	Testing **On** Rolling Stock	Testing **On** Rolling Stock	Testing "*Off* Rolling Stock":	Testing **On** Rolling Stock
Engine power settings:	**All Engine power settings**	Real operating engine idle loads	**All Engine power settings**	Real operating engine idle loads
Engine load source for testing:	Connected to resistive load bank	No external load source required	Fitted to Dynamometer to provide load	No external load source required

5.2 Diesel-electric transmission rolling stock

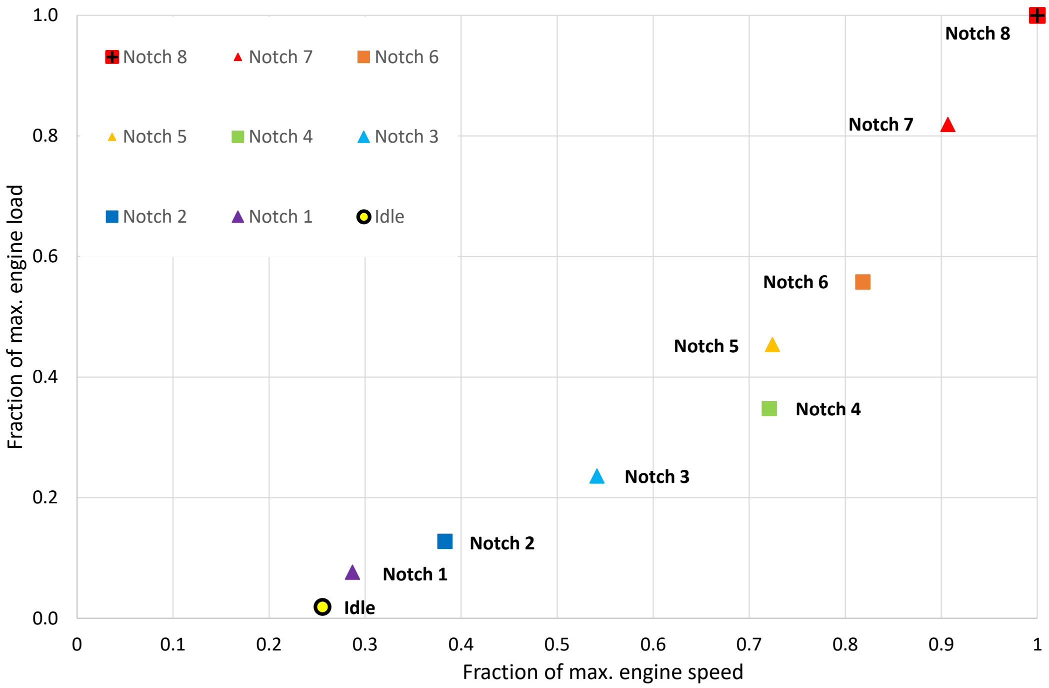
On diesel-electric transmission rolling stock a diesel engine drives an alternator from which alternating current (AC) is converted by a rectifier to direct current (DC) to then feed motor control electronics that drive either DC (on older stock) or AC (on newer stock) traction motors. Some parts of 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.

There are two categories of diesel-electric transmission rolling stock: locomotives and DEMUs. While the engine cannot be easily removed for testing from locomotives, DEMUs use the raft concept whereby on most modern units the engine, cooling system and alternator are on rafts attached to the vehicle underside that can be easily removed for servicing and maintenance. Thus, for DEMUs the engine can more easily be tested off the rolling stock compared to locomotives. Dynamometers are widely available for the small- and medium-sized engines that are typically installed on most DMUs (e.g. Class 150-175, 195-197, 231 and 755/756). DEMUs, such as Class 80x and 220/221/222, have larger engines (e.g. maximum power > 450kW) and thus would require large dynamometers which are not widely available. However, for the Class 80x, and potentially for the Class 220/221/222, engine emissions testing can be carried out while the engine is installed on the rolling stock.

Conveniently, diesel-powered rolling stock with electric transmissions are very close to replicating the dynamometer setup of a traditional static test cell. As an alternator is attached to the engine, only the addition of a resistive load bank (and suitable controls in some cases) and power measuring equipment is required to replicate the dynamometer setup for field-based testing where the engine remains installed on the rolling stock.

Most diesel-electric transmission rolling stock have fixed pre-set throttle levels and engine speed control that corresponds to fixed power outputs (at a given engine speed) usually referred to as notches. Given the relatively constant engine running conditions in a notch, emissions are similarly constant in a notch. Hence, power/notch emissions testing (measured in g/kWh, i.e. emissions per unit power) is potentially very useful and is mandated in the US. GB diesel-electric transmission rolling stock has between 6 and 17 separate notches but typically 9 notches (numbered 0-8). Measurements of emissions at each of those notches are especially useful as they can be combined with real train running data from the OTMR to produce accurate rail emission estimates encompassing variations in engine condition across a complete trip[13]. Results from each test point can also be weighted according to the real usage level of the engine to derive average factors for developing more simplified estimates of emissions.

Figure 5 Example showing actual diesel electric locomotive engine speed and power settings for all notches for a Class 66 locomotive



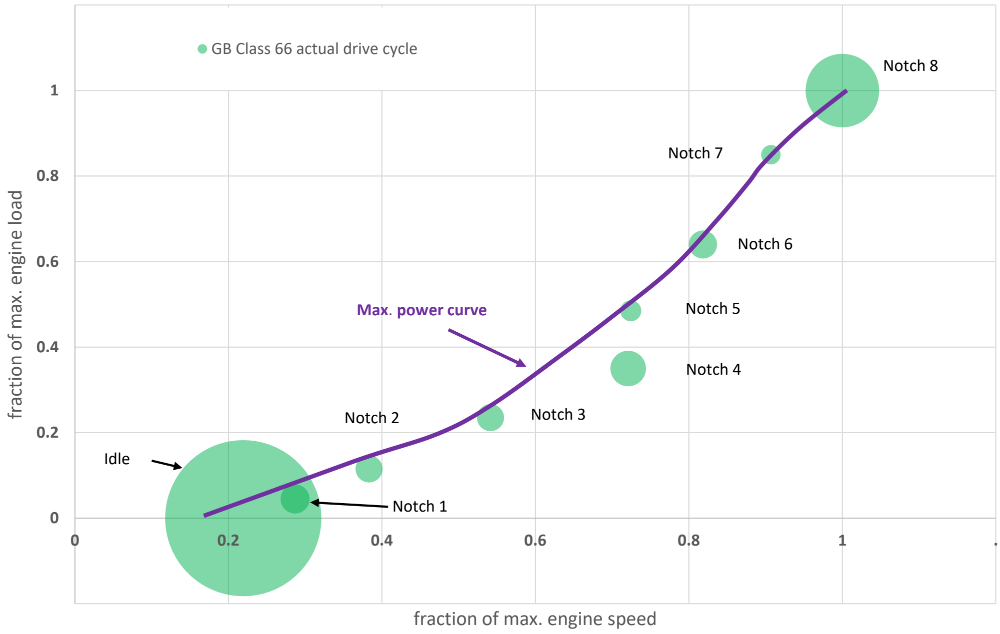
There are many similarities between conducting emission tests on diesel-powered rolling stock with electric transmissions and on diesel engines used for stationary electrical generation. There is already extensive experience in Great Britain of conducting on-train engine performance and reliability testing for rolling stock with electric transmissions under real load conditions at most operators and some external rolling stock maintainers. Typically, such testing is carried out post maintenance to

[13] Grennan-Heaven, N. and M. Gibbs (2020). CLEAR: Fleet-wide assessment of rail emissions factors. RSSB

assesses whether the engine is performing mechanically as expected. The main gap for many operators or maintainers is expertise in engine exhaust emissions measurement.

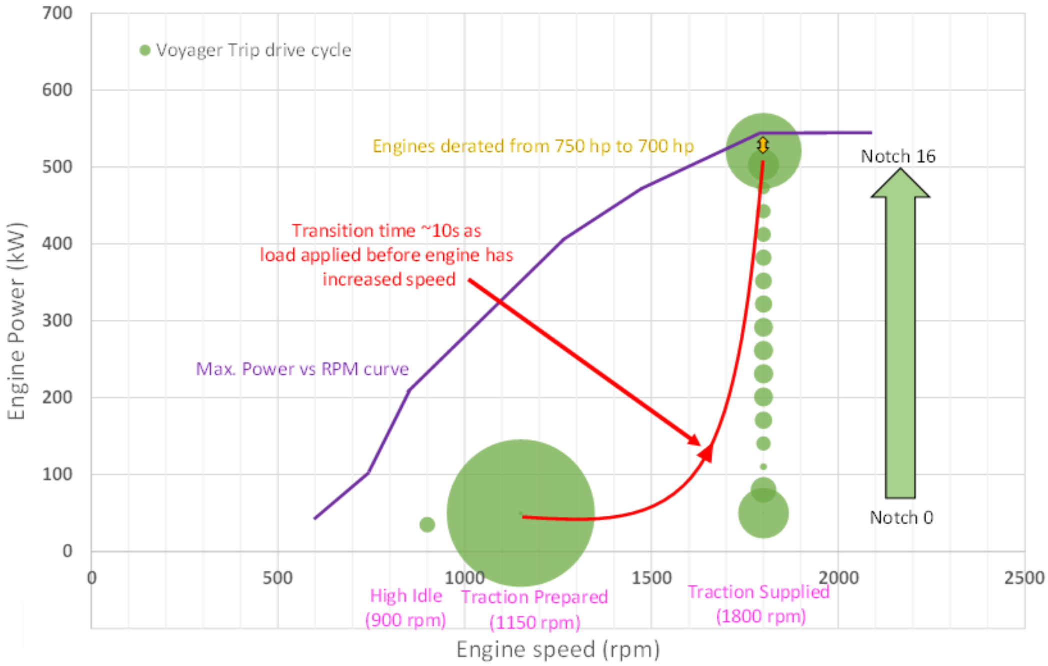
To understand the relative impacts of emission in different notches, time-based drive cycle weighting can be used with the mode test points to understand the relative impact of certain notches on overall emissions. In Figure 6 the time-based drive cycle for Class 66 has been overlaid on the notch settings from Figure 5 as a bubble chart, which highlights the importance of idle and Notch 8 on the overall locomotive emissions.

Figure 6 Example of testing points, with circles representing real drive cycle weightings for Class 66



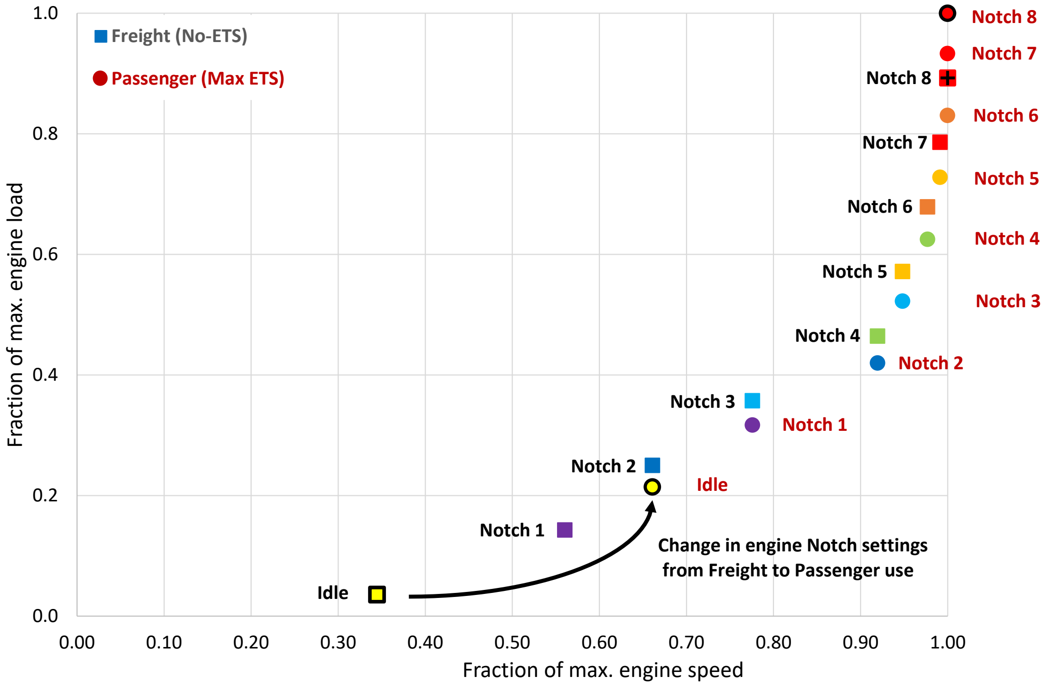
DEMUs are often broadly similar to the locomotive set-up shown in the previous two figures with traction power supplied at a range of different engine speeds. An alternative control set-up approach is to use a “gen-set” type approach where the traction power is supplied at constant engine speed, typically 1,800 rpm, matching the engine speeds for 60 Hz electrical generation as shown in Figure 7. As with locomotives, only a relatively small range of mode test points for emissions testing covers the entire engine operation.

Figure 7 Example showing actual diesel electric multiple unit engine speed and power settings for all notches for a Voyager/Meridian DEMU with the red line showing the typical transient conditions as full traction load is requested from the engine.



Even within rail classes, substantial differences occur. This is particularly pertinent to locomotives that are in both passenger and freight service since freight drive cycles are highly dependent on loads and routes hence disaggregating emission data for test points and the weighting for those test points. Another difference for a locomotive that may be in both passenger and freight service is the engine notch setting in terms of engine speed (rpm) and power. Passenger use has higher auxiliary loads due to ETS for the coaches' hotel load needs (heating and air-conditioning, lighting and power sockets). The locomotive notch setting can therefore vary between freight and passenger use as demonstrated in Figure 8 below which includes the settings for Class 68 in both passenger use (shown with round markers) and freight use (shown with square markers).

Figure 8 Difference in Class 68 test points for freight and passenger use



This difference in auxiliary loads (including hotel loads) results in the need to potentially conduct emission testing for two complete sets of notch settings. However, some of the settings are very similar, albeit for different passenger and freight notches (i.e. same rpm and similar power). Therefore testing both sets of notch settings in full could be avoided: for example, Notch 4 freight setting are very similar to Notch 2 passengers settings, but this would need cooperation between passenger and freight operators so is potential unlikely unless there is a industry wide approach to maximising efficient in testing.

5.3 Diesel-hydraulic transmission rolling stock

For diesel-hydraulic transmission rolling stock 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, ventilation and air-conditioning (if fitted) and lighting as well as radiator cooling fans. The efficiency of the hydraulic transmission is highly variable and dependent on the DMU speed and engine torque.

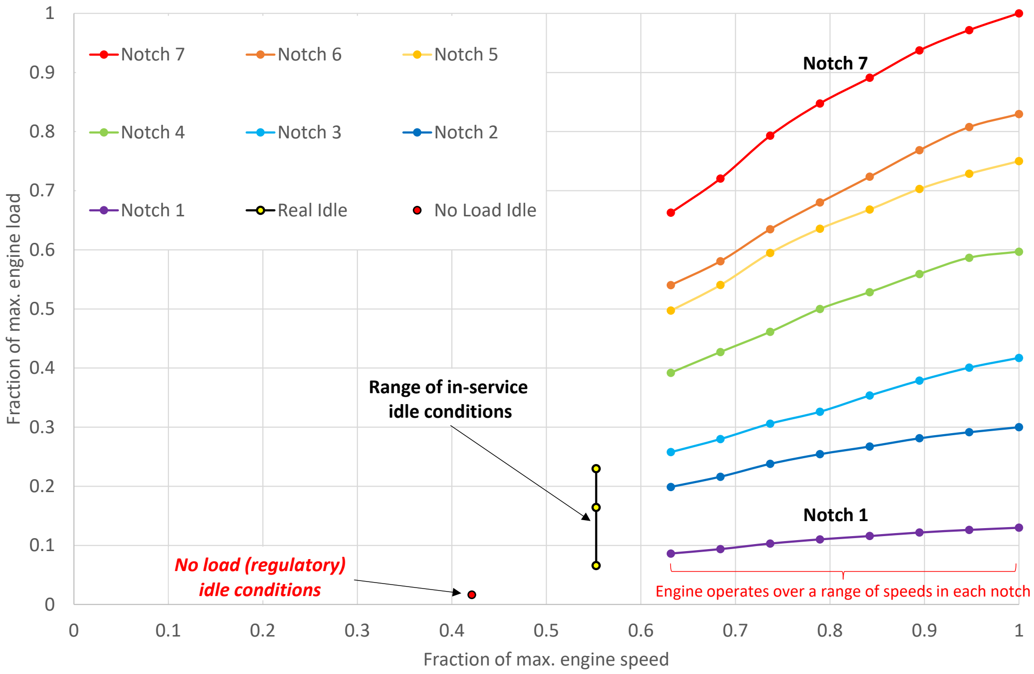
Diesel-powered rolling stock with hydraulic or mechanical transmissions presents a further level of complexity and difficulty for emissions testing in that it is not possible to apply real traction loads and conditions for the engine while it is installed on the rolling stock. Hence while realistic idle conditions can be and are best tested whilst the engine is installed on rolling stock (as real auxiliary loads and idle conditions are inherently available for testing), non-idle engine conditions where traction power is provided can only be tested with the engine connected to a dynamometer in a test cell. The dynamometer allows testing at various engine powers, torques and speeds to be conducted.

Diesel-hydraulic or mechanical transmission rolling stock is somewhat more complex than the diesel-electric transmission equivalents. Such rolling stock has fixed pre-set throttle levels but does not have the combination of fixed engine speeds and power outputs of electric transmission rolling stock. Hence for each notch, emissions testing needs to be conducted for a range of engine speed (rpm) combinations, resulting in a range of values for each notch. The results from each test point can then be weighted according to the real usage level of the engine to derive average notch-based emission factors for a simpler overall approach. Ideally the data from individual test mode points should be retained without aggregation as this would allow more useful detailed and accurate emission modelling to be done without the need to conduct additional emissions testing, for example evaluating how a DMU performs on a new route or stopping pattern. This is easier for more modern engines where interrogation of the engine control unit (ECU) allows the relative time spent at various engine speeds in each notch in real world use to be understood relatively easily. There are other techniques available for the analysis of engine speed for older non-computerised engines (e.g. audio monitoring[14]).

The potentially large number of test modes for diesel-hydraulic or mechanical transmission rolling stock could lead to compromises with either (or realistically both) reduced time spent in each test mode (potentially reducing accuracy of test results) or a reduced sub-set of test modes chosen (resulting in later challenges around interpolation of data from a limited number of test points test points). Figure 9 below shows an example of engine power and speed settings for all notches for a DHMU. Each dot on the Notch 1-7 curves in Figure 9 represents the 50 rpm increments that are being suggested for DMU engine testing in the Testing Protocol.

[14] Grennan-Heaven, N. and M. Gibbs (2020). *CLEAR: Fleet-wide assessment of rail emissions factors*. RSSB.

Figure 9 Example showing diesel hydraulic multiple unit engine speed and power settings for all notches, the dots on the notch 1-7 curves illustrate increments of 50 rpm

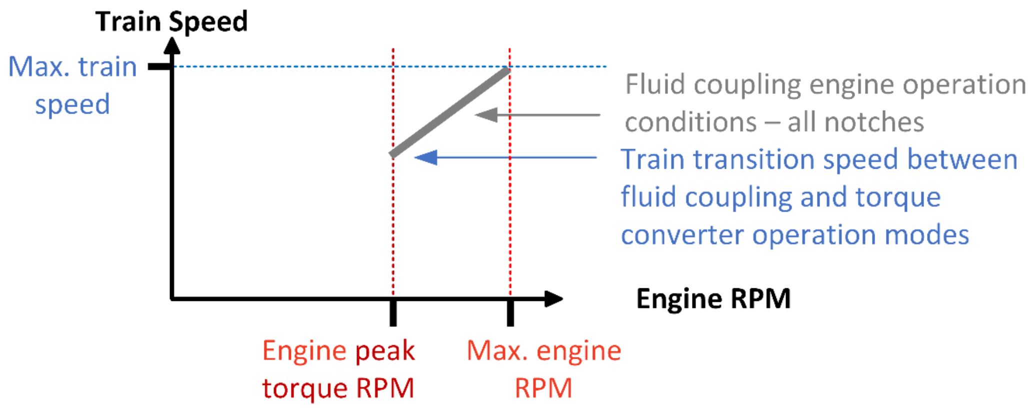


Certain non-idle test mode point conditions will see far more use in real world running than others. It is assumed that testing additional test points in an automated way on many dynamometers (e.g. through pre-programming) will require less work than deciding which mode test points to potentially not test. Increasing the range of test points will also provide extra confidence in test results from each test point if the conditions of the adjacent test results are similar. This should only result in minimal extra fuel costs for DMU engines. If the same engine were retrofitted with a mechanical transmission then the weightings for the test points would change significantly in many cases. Thus, collecting the full set of data is potentially highly beneficial for accurate modelling work, for example, to assess the feasibility before development of retrofit options, as well as retaining flexibility for any future analysis or assessment of mitigation options.

The closeness (in speed and power terms) of many of the potential test modes (as shown in Figure 9) and the comparatively low duty cycle time of many of them means that a reduced number of test modes could be selected for emissions testing. This would potentially represent a small saving of testing effort but would require careful analysis of OTMR data and the expected performance envelope of the potential mitigation solutions in advance of the emissions testing. However, this relatively small saving would need to be balanced against potentially having less data available in the future, while more test points will improve confidence in accuracy through the availability of data under similar test conditions., as the additional testing effort/time is small compared to the testing set up and close out time.

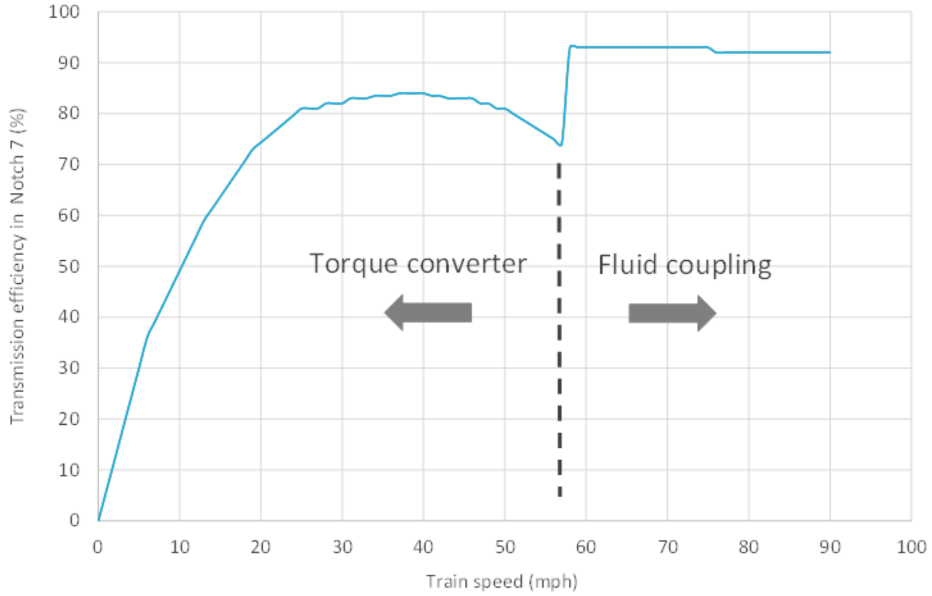
At higher train speeds (typically above 60-65% of the maximum train speed), the hydraulic transmission utilises a very efficient fluid coupling in the transmission to transfer the engine torque to the driveshaft and wheels. The fluid coupling effectively directly links the engine speed to the train speed so there is a direct link between engine rotational speed and train speed (provided there is no wheel slip). The linkage between engine rotational speed and train speed is fixed irrespective of which notch the engine is operating in while in the fluid coupling mode e.g. above a set transition speed. If the throttle setting is changed to idle above the transition speed then the fluid coupling disengages so there is no linkage between the engine and wheels and the vehicle can coast (similar to a car engine with a manual gear box in neutral). The transmission is set up to utilise the fluid coupling between engine peak torque rpm (at the transition speed) and the maximum engine rpm (at the maximum train speed). Engine speed to train speed dependency in fluid coupling mode is illustrated by the grey line in Figure 10.

Figure 10 Engine speed dependency versus vehicle speed dependency in fluid coupling mode



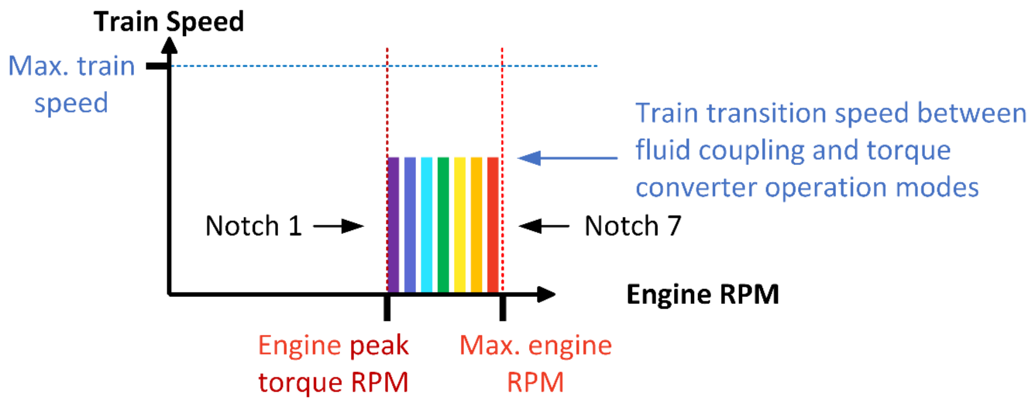
At lower train speeds (typically below circa 60% of the maximum train speed) the hydraulic transmission uses a torque converter to transfer the engine torque to the driveshaft and wheels. It allows the transfer of engine torque to the wheels independently of engine speed when the engine speed would be below the minimum practical rpm for the fluid coupling if that were used. The flexibility of the torque converter comes with a large inefficiency penalty, especially at very low train speeds, which is illustrated in Figure 11. The relative inefficiency is one of the reasons for the current trend in new-build DMUs to use mechanical transmission which improves transmission efficiency in the region between circa 5% and 60% of the maximum train speed.

Figure 11 Transmission efficiency versus speed dependency for hydraulic transmissions (Class 158)



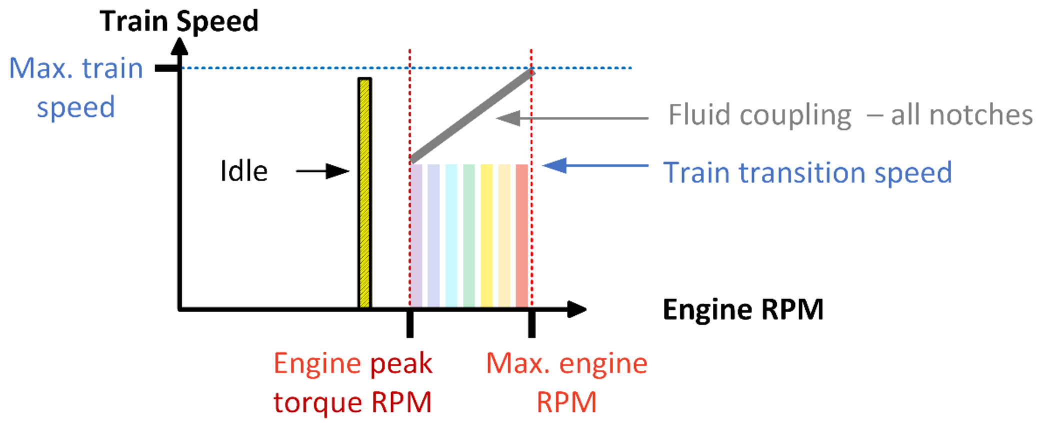
Unlike the fluid coupling operating mode, in the torque converter mode there is no engine speed to train speed relationship. Under stable operating conditions, the engine speed is instead related to the notch setting. Here, the engine is operating at maximum rpm in the highest notch. However, as the notch setting is decreased, the engine speeds also decrease progressively. During this process, the engine rpm in the lowest notch setting will still be at the engine's peak torque speed for a small number of installations. For most rolling stock, it will be above the engine's peak torque speed. The latter is clearer to illustrate and is shown in Figure 12 with the operating condition envelope colour coded by notch. Here, the lowest notch setting in torque converter mode is around the engine's peak torque speed. The engine rpm for the lower notches in torque converter mode on most DHMUs is typically higher than shown in the Figure 12. However, the highest notch rpm will still be at the maximum engine rated operating rpm.

Figure 12 Engine speed dependency versus vehicle speed dependency in torque convertor mode by notch



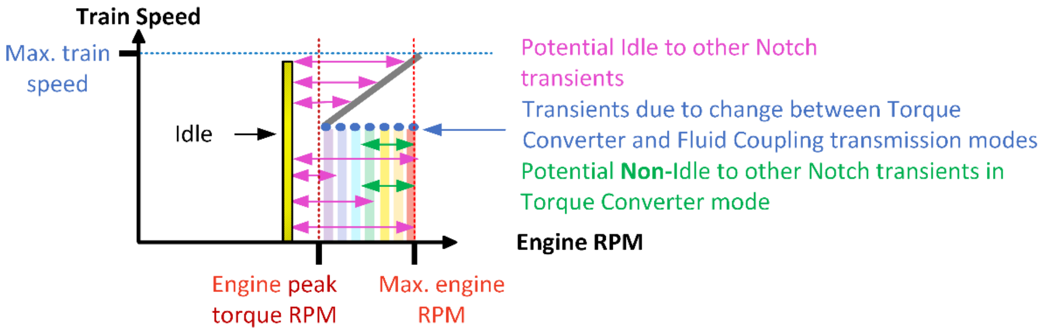
The final parts of the engine and train speed operating envelope are the use of idle and transient operating conditions when the engine is transitioning between notches or transition mode. In idle, the transmission elements are disengaged in both torque converter and fluid coupling modes and there is no linkage between the engine and wheels so the engine speed is constant and independent of train speed, allowing the train to either coast or brake with no impact on engine operating conditions. This is illustrated in Figure 13.

Figure 13 Engine speed dependency versus vehicle speed dependency in idle



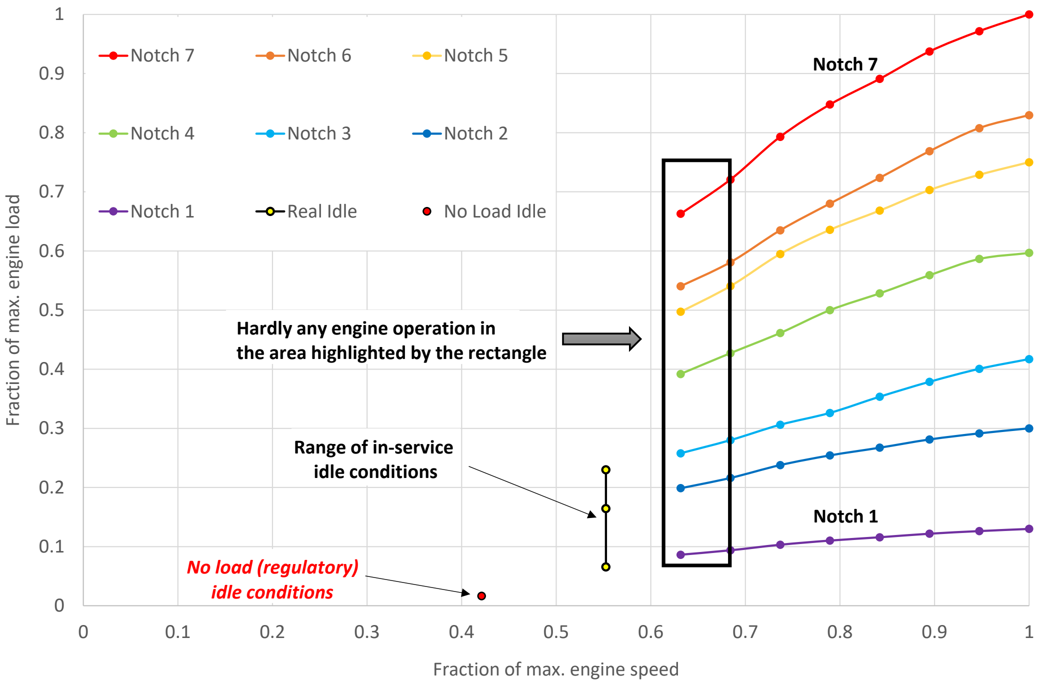
With DHMUs, transients take three main forms. The first is when transitioning from torque converter to fluid coupling mode or vice-versa which is illustrated by the line of blue dots in Figure 14. Transients arising from the transition between notches can take two forms. The most significant transitions between idle and other notches in both torque converter and fluid coupling mode are illustrated by the pink arrows in Figure 14. The less significant occur between Notches 1-7, and are focused in the lower train speed torque converter operation (illustrated by the green arrows in Figure 14).

Figure 14 Engine speed dependency versus vehicle speed dependency under all condition modes by notch



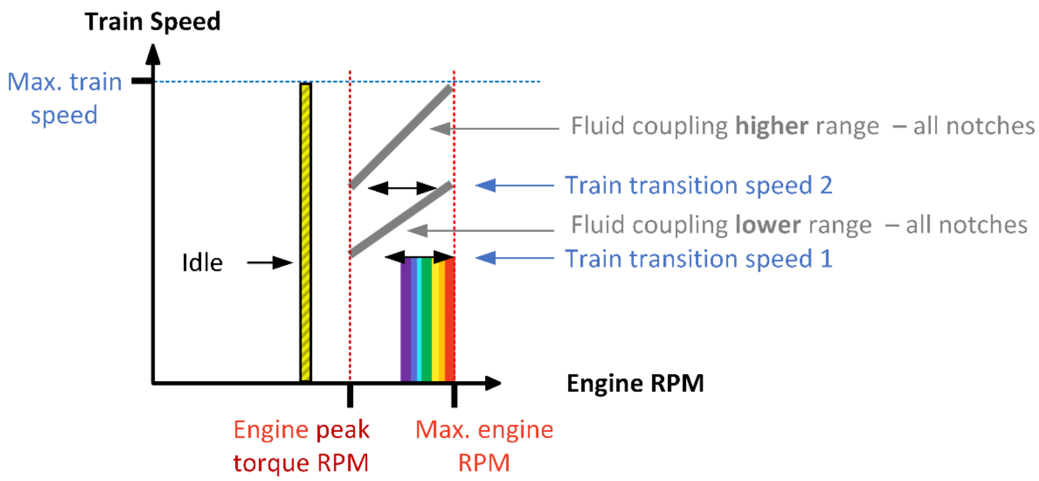
With the hydraulic transmission as set-up on DHMUs, very little engine operation occurs in non-idle notches below the engine peak torque rpm (only short-term transients to/from idle), which provides the potential opportunity to reduce some of the mode test points for emission testing as highlighted by the black rectangle in Figure 15. However, if the hydraulic transmission were to be replaced with mechanical one (see Section 5.4) then there would be some engine operation below the engine's peak torque speed so the operating conditions highlighted by the black rectangle would then need to be included. Many DHMU engines are controlled indirectly via the transmission and are tested post overhaul with a dynamometer attached to the transmission. Hence it would not be possible to test the conditions highlighted by the black rectangle while the engine is attached to the existing transmission.

Figure 15 Engine speed dependency versus vehicle speed dependency under all condition modes by notch



On higher maximum speed or higher performance DHMUs (e.g. Class 180 and 185) there is also the option of adding a simple 2-speed mechanical gearbox to the fluid coupling part of the transmission which is only used in fluid coupling mode, which enables the more efficient fluid coupling to be used over a wider range of train speeds. This would reduce the lowest speed the fluid coupling can operate at from typically above 60-65% of the maximum train speed to around 50% of the maximum train speed. As a result, overall transmission efficiency would be increased by reducing torque converter mode use. This approach is illustrated in Figure 16 where there are two fluid coupling ranges and two transition speeds. With all fluid coupling transmission elements (and the fixed gear ratio elements of mechanical transmissions), there is a fixed ratio between engine and train speeds (assuming no wheel slip or wheel slide) and the gradient of the grey lines in Figure 16 reflect the net ratio of all the fixed gear ratios in the transmission and final drive gearboxes on the axles. As the grey lines on the charts represent these ratios, they would always intersect the origin of the chart if the lines were extended.

Figure 16 Engine speed dependency versus vehicle speed dependency for Voith T312 type transmissions with two fluid coupling ranges created by adding a simple 2-speed mechanical gearbox to the fluid coupling part of the transmission (as used in Class 180 and 185)



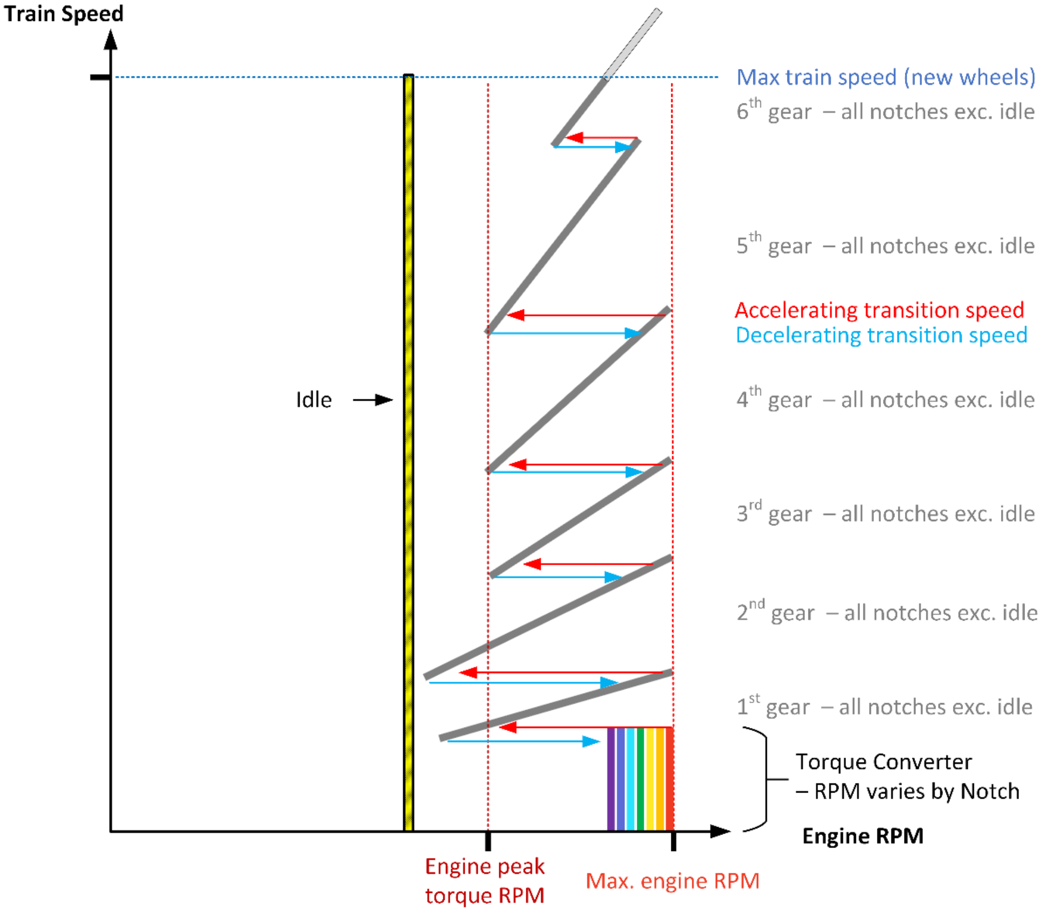
5.4 Diesel-mechanical transmission rolling stock

For diesel-mechanical rolling stock a diesel engine primarily drives a gearbox with 6 or 7 ranges and fixed gear change points which, in the same way as for hydraulic transmission, then drives a final drive gearbox to turn the vehicle wheels. Part of the mechanical power generated drives an air compressor to maintain air pressure for braking and suspension systems and an alternator which provides electrical power for train heating, ventilation and air-conditioning and lighting as well as radiator cooling fans.

The lowest 'gear' in the DMMU gearbox is always a torque convertor but unlike hydraulic transmission 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 for hydraulic transmission. Above 20 mph five or above 15 mph six fixed mechanical gear ratios are used for Classes 172 and 195/196/197, respectively. Some mechanical gearboxes have the ability to select neutral and hence allow coasting (e.g. Class 195/196/197). Other DMMUs do not have a neutral option (e.g. Class 172) and so do not allow coasting in idle, which results in higher fuel consumption and emissions.

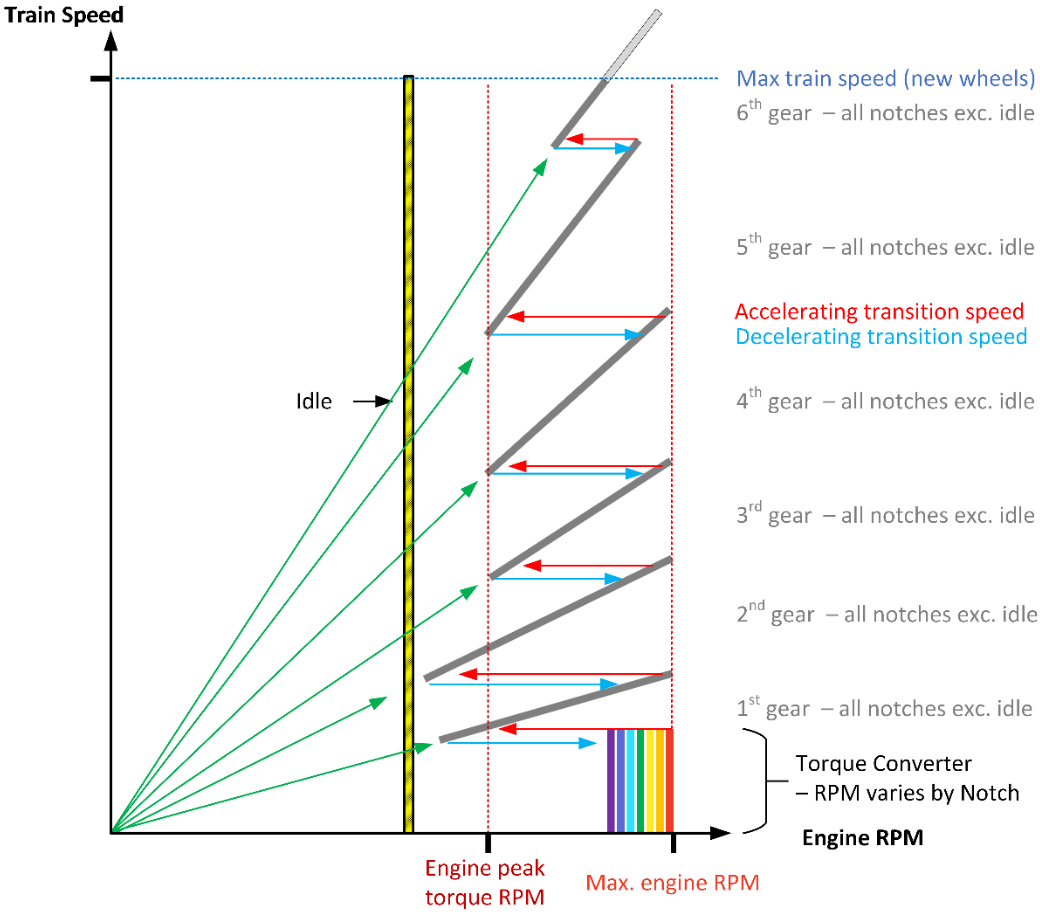
An example of a typical mechanical transmission with six fixed gear ratios and the ability to coast example is shown in Figure 17. As with an hydraulic transmission the torque converter allows transfer of engine torque to the wheels with no linkage between engine and train speeds but with the engine rpm in each notch being relatively fixed in non-transient conditions. Similar to the fluid coupling in DHMUs, in the fixed gear ratio elements of mechanical transmissions there is a fixed ratio between engine and train speed which is the same for all non-idle notches if the gearbox has the coasting configuration (as illustrated in Figure 17). The non-coasting option is illustrated in Figure 21. In order to prevent constant gear changing if the train is to maintain a speed approximately equal to the transition speed between gears, different set transition speeds are used if the train is accelerating or decelerating and these are marked on Figure 17 in red and blue arrows respectively.

Figure 17 Example showing engine speed and vehicle speed relationship for a DMMU



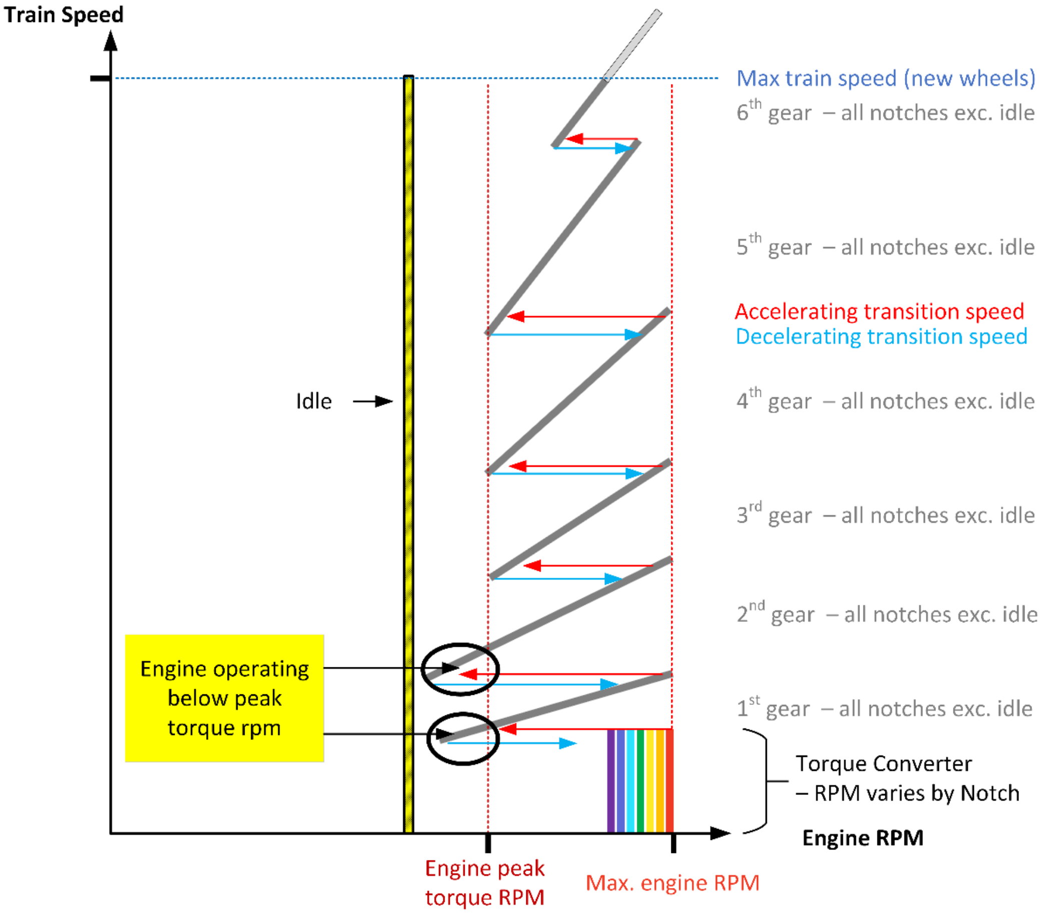
The gradient of each grey line reflects the net ratio of all the fixed gear ratios in the transmission and final drive gearboxes on the axles for that gear. Reduction of the wheel diameter either though wear or wheel turning to maintain wheel geometry will also alter the overall gearing ratios and introduce variability in practice. The grey lines on the charts represent these ratios and would always intersect the origin of the axes on the chart if the lines were extended as illustrated by the green arrows in Figure 18.

Figure 18 Example showing engine speed and vehicle speed relationship for a DMMU



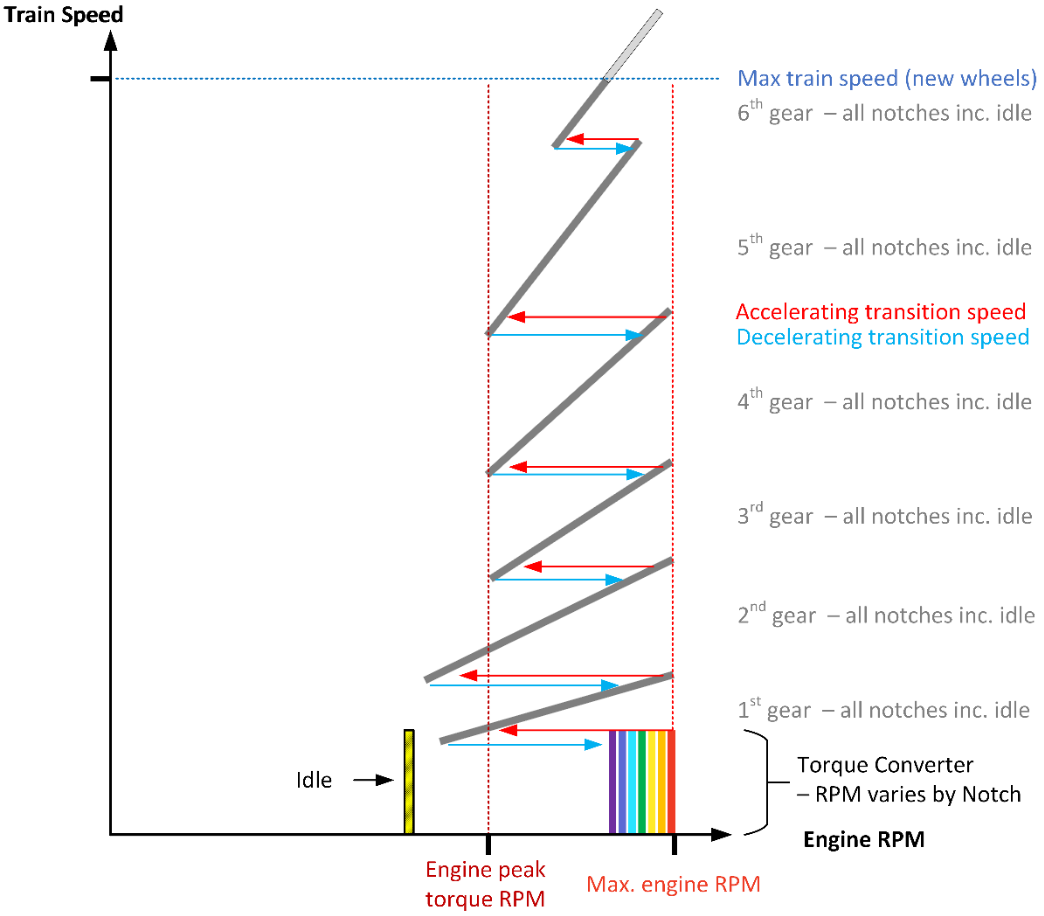
In the higher gears the engine operates in the range between engine peak torque and maximum engine rpm. In first and second gears (at the lower train speeds for those gears) the engine operates below the peak torque point under non transient condition, an operating condition that does not occur with hydraulic transmissions. This situation is illustrated in Figure 19 by the two black ellipses.

Figure 19 Example showing engine speed and vehicle speed relationship for a DMMU



In older mechanical gear box designs (e.g. Class 172) there is no ability to uncouple the engine from the fixed gear ratios to coast in a similar manner to all other existing DHMU/DMMU transmissions. Hence the engine at idle will have the same engine rpm to train speed relationship as the other notches. This is also the case in newer hybrid rafts when the combined alternator/traction motor is being used for regenerative braking and the engine has not been switched off. Both situations are illustrated in Figure 20. As regards emission testing this means there is a far wider set of idle engine speeds (rpm) that need to be considered.

Figure 20	Example showing engine speed and vehicle speed relationship for a DMMU



5.5 Addressing transients

In rail, transients are a minimal contribution to overall emissions when compared to other sectors for example for road vehicles, since changes in power demand are far less frequent in rail. However, some transient engine conditions are potentially significant for station and depot emissions and overall emissions at those specific locations. For example, when engines have been idling for several minutes the effectiveness of SCR at reducing NOx emissions falls off after an extended period in idle as the exhaust temperature is too low for the SCR to operate. Consequently, SCR may be ineffective in high notches as a train accelerates out of a station because the exhaust temperature is not yet high enough.

For simplicity, most transient conditions are excluded from the Testing Protocol because of the minimal impact they have on total emissions. The two most relevant transient conditions that have potential localised emission impact (e.g. at stations) because of their specific significance to exposure in fixed location, can be addressed with using simple scenarios rather than fixed test points are:

- Cold, warm and hot starts (emissions will be higher than normal idle after extended running)
- The cooling of the exhaust system and its effect on emissions after the engine changes to idle as the rolling stock coasts, brakes to a halt, and the engine remains running at a fixed location e.g. replicating the approach to and arrival in a station. In rolling stock fitted with SCR abatement systems the NOx levels will initially be lower than long term steady state idle in the first few minutes, but after the engine and exhaust system starts to significantly cool the emissions will increase. A key aim of the Testing Protocol is to measure the dynamics of this increase in emissions to generate system design data in early testing and transferrable lessons of system effectiveness after installation. This is also relevant for locomotive testing as most locomotives have “cool down” idle modes after extended high power running with different conditions to “normal” or “low” idle modes and this is the only way to replicate the “cool down” idle mode.

These scenarios are easy to include in engine emissions testing if consideration is given during the planning of the sequencing of test points; recommendations are provided in Section 6.2 of the Testing Protocol. However, other location-specific understanding can be adequately developed using data from individual mode test points. For example, for the initial acceleration out of a station, a suitable proxy could be developed by using a representative sequence of test points with time weighting of the test point data. For certain rolling stock at different operators, drivers receive different training on which notch to use for initial acceleration. It will therefore be better to use a modelled proxy for total emissions (based on mode test points and relevant drive cycle weightings) that can be adapted by an operator, rather than a specific fixed testing scenario which may not be relevant to some operators.

6 Relevant data by rolling stock class

6.1 Data requirements

Development of the mode test points for specific rolling stock necessitated compilation of relevant data as shown in Table 2 below. Sources included previous RSSB projects, certain data obtained from industry stakeholders during this project (e.g. additional OTMR data for certain classes, improved auxiliary load data), and audio monitoring of engine speeds during this project.

Table 2 Data availability by rolling stock class

Rolling stock class grouping	Transmission type	OTMR and drive cycle analysis available?	Notch rpm and power settings available (electric transmission only)?	For hydraulic / mechanical transmissions only: notch-based torque and power settings/curves available?	ECU fitted?	ECU data readily down-loadable?	Using audio analysis approach ?	Exhaust temperature data available?	Annual mileage data available ?
150, 153, 155, 156	Hydraulic	Yes		Yes	No	n/a	Yes	Some	Y
158, 159	Hydraulic	Yes		Yes	No	n/a	Yes	Yes	Y
165, 166	Hydraulic	Yes		Yes	No	n/a	Yes	Some	Y
168, 170, 171	Hydraulic	Yes		Yes	Yes	No	Yes	Yes	Y
172	Mechanical	Yes		Yes	Yes	No	Yes	Some	Y
175	Hydraulic	No		No	Yes	No	Yes	Some	Y
180	Hydraulic	Yes		Yes	Yes	Yes	n/a	Some	Y
185	Hydraulic	Yes		Yes	Yes	No	Yes	Some	Y
220, 221, 222	Electric	Yes	Yes		Yes	Yes	n/a	Some	Y
66	Electric	Yes	Yes		Yes	Yes	n/a	Yes	Y
68	Electric	Y (passenger only)	Yes (both)		Yes	Yes	n/a	No	Y
70	Electric	Yes	Yes		Yes	Yes	n/a	Some	Y

6.2 Audio data collection for this project

The majority of the real-world engine condition data required to develop the Testing Protocol was already available from earlier RSSB projects. Where no ECU engine speed data were available, audio monitoring has been used. This has been particularly useful for filling gaps in data, for example Class 175. For Class 68 locomotives in freight service an alternative approach has been used which involved using proxy data in addition to some newly provided summary engine performance monitoring data.

To produce an "engine map" a method was deployed which drew upon well-established techniques already used in the vehicle sector, in particular by Formula 1 racing teams. Detailed engine running condition data does not exist for the majority of older rail engines, and therefore audio monitoring of the exhaust sound has been used in combination with GPS time, speed and location data. This audio monitoring provides two types of data:

- The dominant audio frequency provides an insight into the engine rpm for live data analysis with a high degree of accuracy
- The relative audio power of the dominant frequency can be used to indicate the engine power or notch setting. This is done as a combination of live and post processing.

The main exhaust frequency is a function of the time difference between successive cylinder exhaust valve openings in each exhaust manifold. E.g.:

$$\boldsymbol{E_{RPM} = f_0(Hz) \times \frac{E_{stroke}}{2} \times \frac{1}{E_{cyclinders}} \times \frac{60[RPM]}{1[Hz]} \times k}$$

Where:

E_{RPM} = the engine speed (RPM)

f_0 = the dominant frequency of the exhaust (Hz)

E_{stroke} = whether the engine is 2 or 4 stroke

$E_{cylinder}$ = the number of engine cylinders

k = exhaust geometry factor (usually 1 e.g. for inline 6 cylinder with single exhaust manifold)

All engines with data gaps prior to the project and which were therefore studied using audio monitoring are straight-six engines with a single exhaust manifold. For 4-stroke straight-six engines with a single exhaust manifold the engine rpm is twenty times the main frequency, e.g. if the engine is running at 1,800 rpm, the frequency is 90 Hz.

$$E_{RPM} = f_0(Hz) \times \frac{4}{2} \times \frac{1}{6} \times \frac{60[RPM]}{1[Hz]} \times 1 \rightarrow E_{RPM} = f_0(Hz) \times 20$$

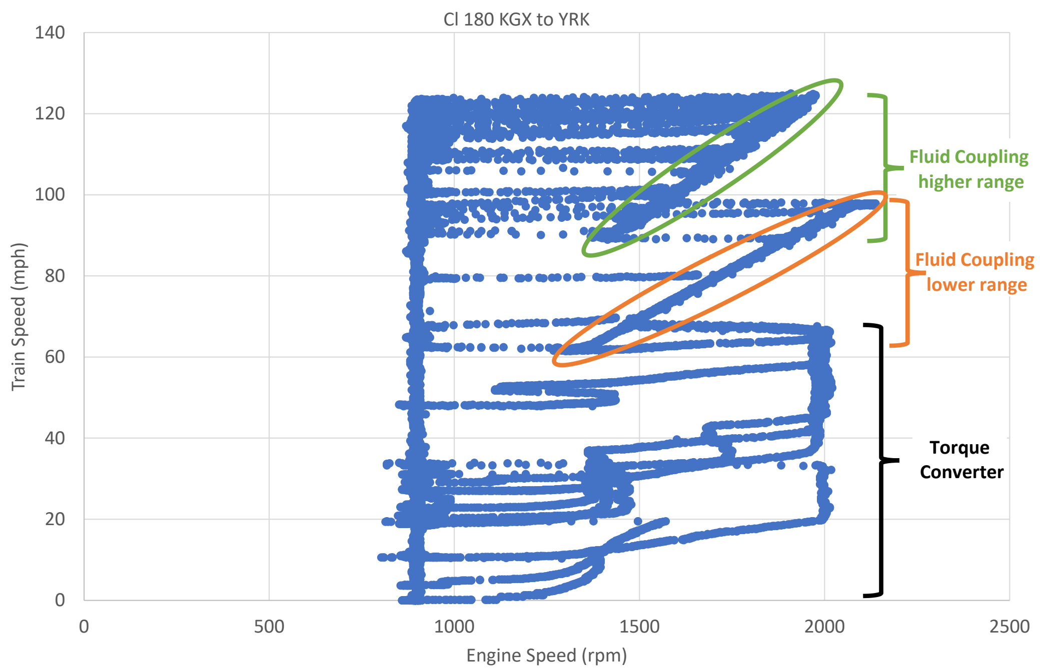
This also applies to the main frequency from twin manifold V12 engines (where each bank of the engine effectively behaving identically to a straight-six which also have higher twin secondary frequencies if the two exhaust streams then merge.

For the detailed audio monitoring, code was developed and has been used for both live and post processing of high-quality audio. This was run on a laptop (with high quality external microphone) while seated in the passenger compartment in DMUs. Python code was used to combine the audio processing and GPS data streams to provide concurrent fundamental audio frequency, time, speed and location information. The audio processing uses discrete cosine transform using either live and/or post processing to output the engine speed. Data were collected every 1/10th of a second to align with the co-recorded GPS location and speed data streams. Audio notch analysis can be performed in post processing and audio volume calibrated for notch settings at certain locations. The onboard in journey audio and concurrent GPS data was augmented with data from phone apps that provide fundamental audio frequency analysis data to fill other data gaps e.g. engine idling rpm in stations when not measuring onboard.

This audio data and time, speed and location information was then aligned with the rolling stock and route combinations for which OTMR data was already available to improve engine power and notch setting understanding. Through this, an “engine map” was produced along with the necessary weightings.

To provide an example as to the kind of detail that can be achieved using this technique, Figure 21 below demonstrates the relationship between engine speed and train speed for a Class 180 train travelling from Kings Cross to York. Each dot on the chart represents 1/10th of a second. There are over 100,000 dots overall on the chart and in some places there are many hundreds of dots overlaid on top of each other. A strong engine-train speed dependency can be observed. Periods of idle can be identified by the vertical line at 800 rpm. Two fluid coupling modes occur, identifiable by straight lines of positive gradient within the green/orange ellipses in Figure 21. Fluid coupling use occurs between the engine peak torque rpm and the maximum engine rpm. The torque converter is in operation when engine speed is around 2,000 rpm (when not control system limited at low speeds, which is identified with the red ellipse within Figure 22).

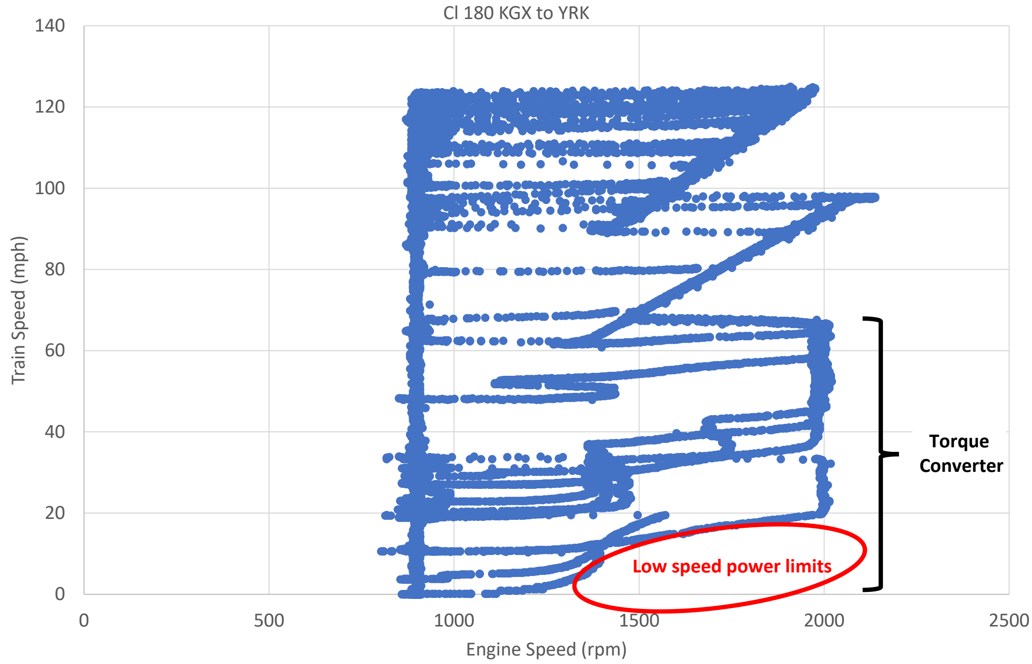
Figure 21 The relationship between engine speed (rpm) and train speed (mph) for a Class 180 train travelling between Kings Cross and York.



This audio monitoring data collection has confirmed that most non-idle engine use is in engine running conditions with typically lower g/kWh NOx and PM emission factors. This is a result of the way the DHMU transmissions with torque converter and fluid couplings are configured, with higher power typically being supplied under cleaner running engine conditions. Non-idle engine use effectively occurs above peak torque speed, resulting in lower emissions in terms of g/kWh and therefore contributing positively to rail's overall emissions picture. For example, for DHMUs engine speeds are typically greater than 1,400 rpm. At higher train speeds (while in fluid coupling mode) the rpm is proportional to train speed. At lower train speeds, typically less than 45-60 mph (depending on rolling stock), the torque converter is utilised and therefore rpm is largely notch dependent. It is worth noting that this recording was made on an intermediate vehicle without an air compressor so the idle speed tends to be constant and lower than on other vehicles where compressors are fitted

At the lowest train speeds where torque converters are particularly inefficient, engines can often supply more power and torque than the torque converter is designed for. On older DMUs this issue is often addressed via driver training which varies by operator (e.g. not to use more than Notch 4 or 5 at less than 10-15 mph). On some more modern DMUs the issue is addressed with logic built into the control systems, as is the case with Class 180s. In that case audio monitoring can help understand how this control logic is setup. The impact of the control logic limiting power at low speeds is illustrated in Figure 22 by the red ellipse.

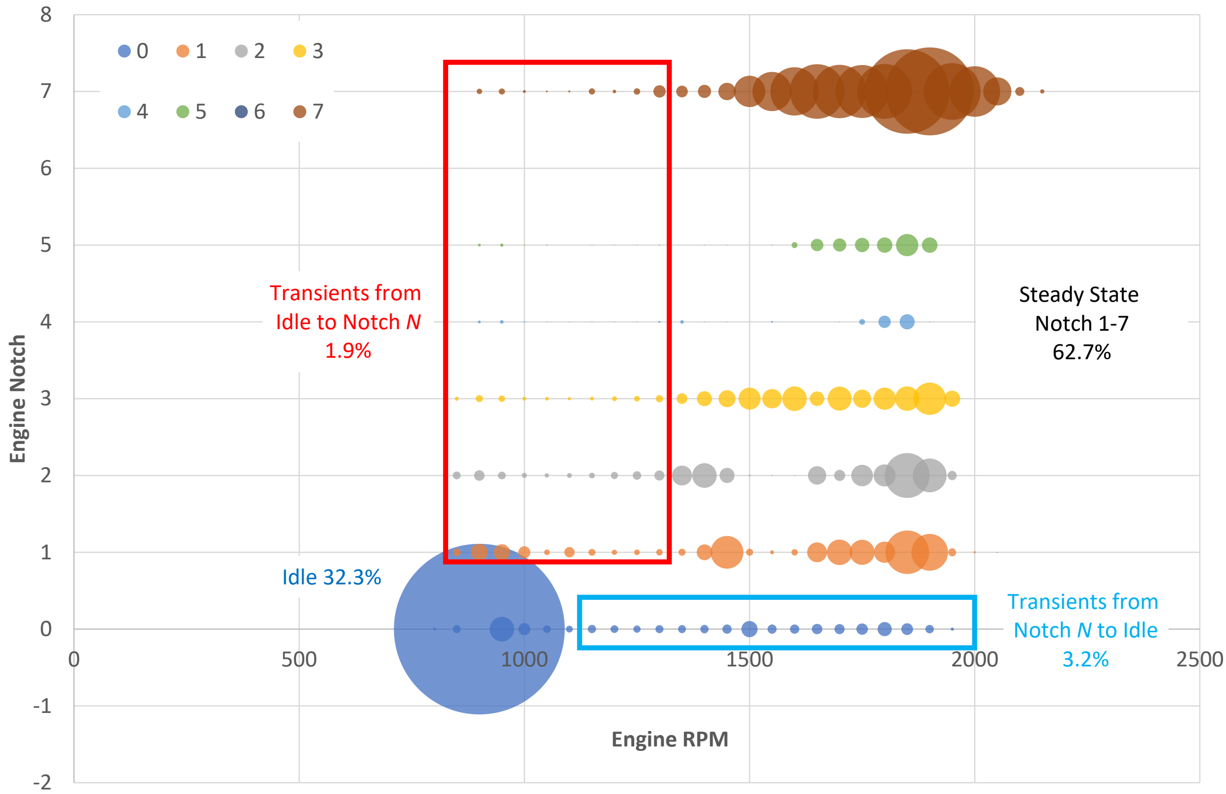
Figure 22 The relationship between engine speed (rpm) and train speed (mph) for a Class 180 train travelling between Kings Cross and York.



In the torque converter case, the total rpm range is less than 250 rpm at the high top-end of engine speeds as reflected in Figures 17-21. Similarly, for DMMUs, low speeds of less than 12 mph also utilise the torque converter, with rpm similar to DHMUs. In higher speeds above 12 mph in gear, rpm is then proportional to train speed *in each gear*. By mostly avoiding the worst operating conditions for emissions when the rail engine is not idling (although not intentionally), the emissions in terms of g/kWh are comparatively lower for rail engines than for the equivalent engine in road transport use.

One of the key steps is to then create a detailed drive cycle based on the engine rpm (from the audio monitoring frequency), engine notch train speed (from the audio monitoring relative amplitude), train speed data from GPS and prior OTMR data from other previous trip for understanding gaps in engine behaviour, aiding interpretation of notch settings and total drive cycles beyond the period of onboard audio recording. These can be combined to create a trip drive cycle as shown in Figure 23 where the rpm data is bucketed into 50 rpm increments. Over this particular trip drive cycle, the total transient conditions are ~5% (contained within the red and blue rectangles), while 95% of the engine running is under stable operating conditions. The proportion of running under stable operating conditions increases when considering the running conditions in the OTMR data for this section of this trip versus wider extended running (including ECS moves and time in depot). This is especially true for idle while in terminus stations and depots, as these locations are under-represented in the proportion covered by audio monitoring for this project.

Figure 23 The relationship between engine speed (rpm) and notch for a Class 180 train travelling between Kings Cross and York.



Drive cycle weightings for all rolling stock types and engine/transmission variants in scope for the project were derived by blending the audio and OTMR data together and are provided in the associated Spreadsheet 1.

The OTMR data coverage varies by rolling stock type and in some cases can encompass many months, allowing an accurate understanding of the total representative drive cycle, including on a speed and notch basis. The detailed analysis from the audio data of engine running conditions by speed and notch provides the engine speed data that can then be applied to the OTMR data to characterise the expected engine speed. From the audio data notch is inferred from analysis post data collection with understanding added from existing OTMR from services on the same routes. For future conditions post mitigation option installation where the test mode points and/or drive cycle weightings may change, design data for these options can be used to derive new drive cycle weightings.

7 Required facilities, capabilities and equipment

The main capability gap across the rail industry and the relevant supplier base is a lack of emissions testing equipment within the rail industry combined with a lack of rail-specific testing experience in the external supplier base.

Three key elements are needed for successful rail emissions testing:

- A dynamometer for off-vehicle DMU engine testing or an electrical load bank for locomotive or certain DEMU engine testing
- Emission testing equipment
- Practical experience of rail emissions, with an awareness that electronic data streams are often not available from the vast majority of rail engines (unlike newer road engines).

Dynamometers are widely available for small and medium sized DMU engines. For larger DMU engines rated above 400 kW, such as those used in Classes 180 and 185, there is more limited number of suitable dynamometers available in the UK. A large dynamometer would also be required for Classes 80x and 220/1/2 but in these cases testing can be carried out on the rolling stock provided an electrical load bank is available.

Most locomotive operators and several overhaul facilities have suitable loadbanks for locomotive testing which are already used for non-emissions engine testing.

Details on required emission testing equipment are provided in the Testing Protocol.

A large number of organisations and facilities will be capable of carrying out the testing required provided that the overall task is suitably split between organisations with emissions testing and engine testing capabilities. RSSB is able to provide a list of relevant organisations and facilities upon request.

8 Considering emission reduction targets

Please note, this section has been developed with minimal industry data on the performance of emissions mitigation solutions in a rail application. This means that precise and stretching emissions reduction targets cannot be set with a high degree of confidence. Therefore, the thresholds outlined in this section should be treated as initial guidance and final thresholds will need to be set depending on the final application of the Testing Protocol developed in this project.

Emissions reduction targets for rail should be challenging but not overly restrictive. Assessing emissions reductions using real world drive cycles may lead to a smaller emissions reduction than expected, especially for those mitigation solutions which are temperature dependent. This is largely due to rail having a higher proportion of time in idle where exhaust temperatures are cooler compared to other sectors. It is therefore better to be realistic rather than overly optimistic when setting emission reduction targets for rail emissions mitigation solutions by defining smaller and realistic emission reductions that are likely to be achievable. In many cases, large reductions in emissions are not required to provide acceptable levels of air quality and the required emissions reduction will depend on the air quality situation being addressed.

The original, pre mitigation emissions level has a significant bearing on the overall impact that a percentage reduction target has and the actual emissions post-measure are potentially far more relevant than how the reduction is defined. It may therefore be better to define the emission reduction targets based upon the desired emissions outcome and back calculate them. In this frame of thinking, what is required to solve the air quality problem is first considered before solutions, targets and thresholds are then proposed.

The nature of reduction targets could potentially take several forms, including of absolute thresholds or percentage reductions. Alternatively, “indirect targets” which focus on actions that result in emissions reductions, for instance reducing quantity of the time engines are idling (particularly in station areas), may be simpler and more appropriate than direct emission reduction targets.

At the moment the quality of the emissions testing baseline data is not sufficient to set precise and stretching emissions reduction targets. Targets may therefore need to be conservative to be achievable in practice and could be raised to higher thresholds when more data becomes available. For example, installation of SCR will be effective where the exhaust temperature is high, during or immediately after the engine has been running in higher notches. However, for engines in rail use the relative proportion of time in these engine conditions is lower than for engines used in other sectors. Hence the maximum theoretical effectiveness of SCR will be lower compared to other sectors. Furthermore, there is not currently enough available data to assess the effectiveness in practice as this will vary by route and service pattern. Consequently, targets may have to be set on a specific application basis. Similar conclusions have been derived from the bus sector for new and retrofit SCR emissions reduction performance. Theoretical expectations of greater than 70% reduction in NOx emissions needed to meet target exhaust emissions levels were not consistent with results for specific bus routes and drive cycles where reductions were found to only be 45-50% in London and Edinburgh[15].

At this time it is only possible to define very conservative targets for many mitigation options. Substantially more baseline data are needed to understand engine operating conditions and the potential for reductions in particular conditions encountered in rail.

The table below provides realistic reductions targets over the whole drive cycle for appropriate groupings of mitigation options and rolling stock classes. When further data becomes available, more stretching targets may be set to ensure air quality benefits are maximised.

Table 3 Recommended conservative emissions reduction targets for different mitigation solutions across the whole drive cycle

Mitigation option	NOx reduction target	PM reduction target
Best available crankcase breather filtration	n/a	>10% for pre-Stage IIIA engines
Selective catalytic reduction (SCR)	50%	n/a
Diesel Oxidation Catalyst (DOC)	n/a	40%
Diesel particulate filter (DPF)	n/a	90% (with DOC)
Exhaust gas recirculation (EGR)	15%	n/a
Timing retardation	5%	Minimal
High pressure fuel injection	5%	<5%
Engine remap	Solution and rolling stock dependent	Solution and rolling stock dependent
DMU battery hybrid – mechanical or electrical transmission	10-15% of residual NOx after SCR	10-15% of residual NOx after DOC & DPF

[15] Carslaw, D.C., M. Priestman, M.L. Williams, G.B. Stewart, and S.D. Beevers (2015). Performance of optimised SCR retrofit buses under urban driving and controlled conditions, Atmospheric Environment, vol. 105, pp. 70-77.

Mitigation option	NOx reduction target	PM reduction target
High functionality shore supplies	Solution and location dependent	Solution and location dependent
Improved turbocharger	10% for pre-Stage IIIA engines	10% for pre-Stage IIIA engines
Charge air cooling	5%	n/a
New engine (compliant with current regulations)	Depends on existing engine emissions compliance status (e.g. unregulated to Stage V: 75%)	Depends on existing engine emissions compliance status (e.g. unregulated to Stage V: 95%)
Alter transmission fixed gearing ratio	Solution and route dependent	Solution and route dependent
Selective engine shutdown (DMU)	<10% (but highly effective in stations)	<10% (but highly effective in stations)
Bi-mode propulsion	Solution and route dependent	Solution and route dependent
Battery electric multiple unit (BEMU)	100%	100%
New traction electrical equipment	Depends on existing configuration (e.g. DC to 3-phase AC: >7%)	Depends on existing configuration (e.g. DC to 3-phase AC: >7%)
Electric-powered compressors and battery upgrades	<10% (but highly effective in stations)	<10% (but highly effective in stations)
Alternative fuels: hydrogen, liquid natural gas (LNG)/compressed natural gas (CNG), hydrotreated vegetable oil (HVO), Fischer-Tropsch process drop-in diesel substitutes fuels, emulsified diesel	Depends on individual fuel	Depends on individual fuel

8.1 Emissions reduction targets in the context of idle

Although idle is a large proportion of the drive cycle and the rate of emissions (on a grams per hour basis) is lower comparted to other notches, these emissions have a far higher impact on passenger and staff exposure in stations. Both absolute and percentage reduction targets would not effectively address this issue and in this case an indirect target focusing on engine shut down (either by training and procedures or by technological means) may be more suitable.

8.2 Acceptable increases in other gases

To ensure that the targets set for NOx and PM do not result in significant increases in greenhouse gases, CO_2, N_2O, HC and methane should be monitored, and targets are required for these pollutants as well. CO_2 monitoring is already required for accurate measurements. Since theoretically none of the emissions mitigation options considered for this project will result in significant increases in CO_2, a target of <5% across the full drive cycle is suggested. Although it could be argued that CO_2 should not be allowed to increase at all, the reality is that test to test variation may result in the post mitigation test reporting a higher CO_2 result and therefore a small acceptable increase should be allowed when comparing pre and post test results.

For other greenhouse gases, it is important that good measurements of N_2O and methane are made before any targets can be set to ensure that the relationship between emissions of air quality pollutants and such greenhouse gases is established. The only mitigation options liable to increase emissions of CO and HC (including methane) are the dual fuel options involving LNG and CNG. In this case targets of <15% increases for CO and HC would be reasonable. In order to ensure that any mitigation measures do not result in a significant degradation on CO_2 equivalent (CO_{2eq}) emissions, the CO_{2eq} of any measured N_2O or methane emissions should be calculated and not lead to an overall CO_{2eq} penalty of 5%.

Therefore taking into account potential CO_2 variation through test to test variability and also taking into account CO_{2eq}, emissions a final overall threshold of 10% for CO_{2eq} emissions should be applied.

Please note: The accompanying research undertaken in the RSSB 'T1236 – Rail emissions mitigation – incentivisation feasibility study' has monetised the relative air quality and CO_2 impacts of difference mitigation technologies and may therefore provide more data on performance thresholds and acceptable penalties.

9 Adapting the emission testing protocol to different circumstances

The Testing Protocol must be able to adapt to different conditions and enable modelling of emissions both before and after a mitigation option is implemented. In this section example current and future test points are discussed.

9.1 Existing test points and weightings

Test points are mainly defined by combined OTMR and audio monitoring data, which help to inform the steady state testing required. Example weightings for a locomotive and a DHMU are shown in the tables below.

For locomotives and DEMUs there are relatively few notches and the engine speed (rpm) is constant for each notch. Example weightings for locomotive test mode points are shown below in Table 4. For DHMUs and DMMUs there are far more mode test points for the non-idle modes so there are weightings by both notch and rpm. The combined weightings for all Idle and Notch 7 test mode points are over 90% in the example in Table 5 (note that these default weights assume the DHMU operating on routes at its maximum permitted speed, the weighting would be somewhat different if the DHMU were always running on route with much lower line speeds). The example in Table 5 is for an engine with a maximum operating rpm of 1900. A number of DHMU/DMMU engine designs have higher maximum operating rpm of either 2000 or 2100, hence the equivalent tables for those engines with have more columns for higher rpm.

Table 4 Example weightings for locomotive test mode points

Class	Low Idle	Normal Idle	Cooldown Idle	Notch 1	Notch 2	Notch 3	Notch 4	Notch 5	Notch 6	Notch 7	Notch 8
66	36.2%	17.3%	16.2%	2.4%	2.1%	2.1%	3.6%	1.3%	2.3%	1.1%	15.5%

Table 5 Example weightings for DHMU test mode points for an engine with a maximum operating rpm of 1900

			RPM																						
		Notes	1900	1850	1800	1750	1700	1650	1600	1550	1500	1450	1400	1350	1300	1250	1200	1150	1100	1050	1000	950	900	850	800
Notch 7	Whole usage drive cycle weightings	% time	6.02%	-	0.71%	1.08%	0.81%	0.93%	0.93%	0.84%	1.25%	1.05%	1.15%	0.66%	0.93%	0.92%	0.71%	0.43%	x	x	x	x	x	x	x
Notch 6		% time	-	0.47%	0.00%	-	0.00%	-	-	0.00%	0.00%	-	0.01%	0.01%	0.03%	-	-	0.00%	x	x	x	x	x	x	x
Notch 5		% time	-	1.35%	-	0.00%	0.00%	0.00%	0.00%	-	0.00%	-	0.00%	0.00%	0.00%	-	-	-	x	x	x	x	x	x	x
Notch 4		% time	-	-	0.58%	0.00%	0.04%	0.28%	0.08%	0.19%	0.15%	-	0.00%	0.05%	0.03%	0.02%	-	-	x	x	x	x	x	x	x
Notch 3		% time	-	-	-	1.71%	0.01%	0.09%	0.00%	0.22%	0.00%	0.00%	0.00%	0.00%	0.01%	0.12%	-	-	x	x	x	x	x	x	x
Notch 2		% time	-	-	0.00%	0.00%	0.72%	0.44%	0.02%	0.02%	0.09%	-	0.11%	0.10%	0.01%	0.12%	0.00%	0.00%	x	x	x	x	x	x	x
Notch 1		% time	-	-	0.00%	0.00%	0.05%	0.40%	0.05%	0.03%	0.03%	0.00%	0.18%	0.16%	0.14%	0.00%	0.00%	0.01%	x	x	x	x	x	x	x
Notch 0 - High		% time	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	34.47%
Notch 0 - Average		% time	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	25.09%
Notch 0 - Low		% time	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	13.74%

9.2 Adapting for future test points and weightings

Some mitigation options will change the drive cycle after installation. For example, battery hybrid solutions that involve greater engine shut down in station areas would involve less time in idle in the new drive cycle. Such solutions may also involve longer running time in higher engine powers in other locations as batteries are recharged. Another example would be use of more stop-start on locomotives or DMUs which would reduce the proportion of time in idle, increase the proportion of time in other engine notches, increase the power requirement and average load at idle and increase warm start transients. Therefore, the Testing Protocol should allow the user to appropriately alter the weightings to reflect future operating conditions. An example of a simple case where there is just change in weighting but no change in mode test point from the existing settings in Table 6 for a Class 170 with greater engine shut down.

Table 6 Example revised mode test point weightings for a Class 170 idle reduction solution

			RPM																						
		Notes	1900	1850	1800	1750	1700	1650	1600	1550	1500	1450	1400	1350	1300	1250	1200	1150	1100	1050	1000	950	900	850	800
Notch 7	Whole usage drive cycle weightings	% time	8.29%	-	0.98%	1.49%	1.11%	1.29%	1.29%	1.16%	1.72%	1.44%	1.58%	0.91%	1.27%	1.27%	0.98%	0.59%	x	x	x	x	x	x	x
Notch 6		% time	-	0.652%	0.000%	-	0.001%	-	-	0.000%	0.001%	-	0.010%	0.017%	0.047%	-	-	0.001%	x	x	x	x	x	x	x
Notch 5		% time	-	1.859%	-	0.001%	0.002%	0.001%	0.001%	-	0.001%	-	0.000%	0.001%	0.002%	-	-	-	x	x	x	x	x	x	x
Notch 4		% time	-	-	0.794%	0.001%	0.058%	0.381%	0.110%	0.265%	0.201%	-	0.000%	0.067%	0.042%	0.023%	-	-	x	x	x	x	x	x	x
Notch 3		% time	-	-	-	2.355%	0.007%	0.128%	0.002%	0.298%	0.004%	0.001%	0.004%	0.004%	0.009%	0.163%	-	-	x	x	x	x	x	x	x
Notch 2		% time	-	-	0.005%	0.002%	0.991%	0.606%	0.022%	0.021%	0.126%	-	0.147%	0.133%	0.020%	0.161%	0.002%	0.003%	x	x	x	x	x	x	x
Notch 1		% time	-	-	0.005%	0.004%	0.072%	0.545%	0.064%	0.041%	0.041%	0.001%	0.252%	0.219%	0.194%	0.004%	0.002%	0.007%	x	x	x	x	x	x	x
Notch 0 - High		% time	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	30.47%
Notch 0 - Average		% time	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	21.09%
Notch 0 - Low		% time	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	11.74%

In some cases the mode test points will need to be changed when a mitigation option is installed to accurately reflect the new engine's operating regime and its emissions. For a Class 170 retrofitted with mechanical transmission and assuming the unit running at maximum, unit speed for at least some of it time, changes to the test point weightings would be required, as shown in Table 7. The range of mode test points that have non-zero weighting increases significantly as does the proportion of Notch 1-7 running at the five lowest rpms and two highest rpms in Table 7 with much more engine running at the rpm in the middle of the range. The changes in expected running conditions and hence weightings just by changing the transmission would be expected to reduce PM, very slightly reduce NOx and CO and increase HC (excluding taking into account any performance advantage of the mechanical transmission which ultimately leads to more coasting, greater use of lower notches reducing fuel use and CO_2 as well as further emissions reductions.)

Table 7 Example revised mode test point weightings for a Class 170 with mechanical transmission

			RPM																						
		Notes	1900	1850	1800	1750	1700	1650	1600	1550	1500	1450	1400	1350	1300	1250	1200	1150	1100	1050	1000	950	900	850	800
Notch 7	Whole usage drive cycle weightings	% time	1.03%	1.93%	1.87%	1.58%	1.79%	2.65%	2.38%	2.05%	1.27%	1.46%	0.22%	0.04%	0.04%	0.06%	0.02%	0.03%	x	x	x	x	x	x	x
Notch 6		% time	0.01%	0.11%	0.03%	0.01%	0.02%	0.03%	0.03%	0.07%	0.05%	0.05%	0.01%	0.03%	0.02%	0.04%	0.01%	0.01%	x	x	x	x	x	x	x
Notch 5		% time	0.09%	0.57%	0.05%	0.01%	0.04%	0.05%	0.03%	0.11%	0.06%	0.10%	0.06%	0.05%	0.02%	0.06%	0.03%	0.03%	x	x	x	x	x	x	x
Notch 4		% time	0.26%	0.17%	0.46%	0.14%	0.07%	0.01%	0.01%	0.11%	0.04%	0.04%	0.03%	0.02%	0.01%	0.03%	0.00%	0.01%	x	x	x	x	x	x	x
Notch 3		% time	0.11%	0.27%	0.11%	0.50%	0.01%	0.08%	0.02%	0.11%	0.08%	0.54%	0.17%	0.06%	0.06%	0.06%	-	-	x	x	x	x	x	x	x
Notch 2		% time	0.34%	0.17%	0.07%	0.10%	0.09%	0.01%	0.12%	0.21%	0.09%	0.46%	-	-	0.02%	0.00%	0.00%	-	x	x	x	x	x	x	x
Notch 1		% time	0.10%	0.13%	0.02%	0.07%	0.02%	0.13%	0.11%	0.32%	0.14%	0.05%	0.00%	0.01%	0.00%	0.03%	-	-	x	x	x	x	x	x	x
Notch 0 - High		% time	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	30.47%
Notch 0 - Average		% time	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	21.09%
Notch 0 - Low		% time	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	11.74%

10 Through-life testing

The purpose of though-life testing is to understand how the emissions from an engine increase as engine with engine usage and secondly how the rates of increase of specific emission are altered by potential mitigation measures. Testing at the end of an engine's working life just before major overhaul presents a relatively simple, easy and the cheapest opportunity to gather some through-life emission testing data for both locomotive and DMU engines. As in the US, locomotive engines in GB rail typically have injectors replaced mid-working life. This presents an opportunity to gather mid working life emission data in a similar way to the US with the smallest possible impact.

For through-life testing, a small number of the same engines (likely fewer than 1%) should be tested at various points through their full working life, including between overhauls. Testing a small number of engines will minimise the amount of overall testing that is required, but the testing frequency will ensure that sufficient data is collected to aid decision making.

Gathering start and end of working life emissions data for DMU engines is relatively straightforward as the engine will already be at overhaul facility with a suitable dynamometer. Gathering mid-working life emission data for DMU engines presents a bigger challenge as there is no testing opportunity equivalent to that for locomotive engines, and the effort and impact on the operator of emission testing DMU engines is far greater. In most cases (i.e. apart from a few DEMU engines), the engine would have to be removed from service and transported to a test facility leaving the whole DMU out of service. This leads to two potential approaches to avoid conducting mid-working life DMU engine emission testing:

- Conservatively assume a linear increase in emissions from start of working life to end of working life, the actual increase in emissions at mid-working life will be lower than this.
- Test one or two DMU engine types at mid-working life and use the data gathered to make assumptions on other engine types. This data would need to be available industry-wide and the shape of the degradation curves for some pollutants could be significantly different if abatement aftertreatment solutions are fitted.

Expectations for increases in emissions over engine working life will vary by pollutant, for example minimal change for CO but up to a 50% increase in PM emissions by the end of engine working life, so the focus should be on pollutants with significant through-life increases (i.e. PM, NOx and HC). Furthermore, the largest part of increases can be expected in the latter part of the engine working life so assuming a linear increase will be a conservative assumption.

11 Recommendations

This section provides recommendations on key issues to improve emissions reduction capabilities across the rail industry and ensuring effective ongoing performance of certain mitigation options.

11.1 Library of baseline testing results

To date, rail emissions testing has been conducted on a fragmented, uncoordinated basis, with developers of mitigation solutions, operators and rolling stock companies carrying out their own testing for particular projects, the results of which are then not published. Consequently, a substantial amount of testing, particularly of rolling stock in its existing ("as-is") condition, is often unnecessarily and wastefully repeated.

Making the results of at least the baseline (pre-installation of a mitigation solution) testing for a range of rolling stock widely available in a library of baseline testing results would have numerous benefits, provided such testing was thoroughly documented and carried out to a high standard. A particular benefit would be providing understanding to all relevant parties of whether a particular mitigation solution would be suitable and effective before design and development were started. However, a challenge is that currently one industry stakeholder pays for the testing, whereas if the results were published benefits could accrue across multiple parties. Consideration may therefore need to be given to a funding mechanism to support, archive and publish such results.

Initiatives by the California Air Resources Board (CARB) to address rail emissions may well be instructive. The State of California funds research and development projects which assess emissions reductions in practice, as well as research into whether a product is reliable before recommended (or required through regulation) for fleetwide implementation. Importantly, CARB has engaged in collecting baseline data, such as on exhaust temperatures, as well as evaluating specific solutions, to fill identified data gaps in partnership with operators and manufacturers. If such baseline testing, intended for use throughout the GB rail industry, were to be funded on an industry-wide basis, then use of the full set of testing points specified in Testing Protocol is recommended. This would include the optional last set of dynamic scenarios that are required to evaluate the effectiveness of SCR.

11.2 Standards for ensuring ongoing emissions performance

Certain mitigation options require ongoing maintenance and monitoring to ensure the mitigation process does not degrade after installation, whereas other mitigation solutions, if installed correctly, do not require intensive monitoring while in use. This is particularly the case for SCR where dosing of exhaust stream with AdBlue, a synthetic urea, at an optimum level is necessary to convert nitrogen oxide to steam and hydrogen. Potential downsides are that limited dosing would render the SCR system ineffective at reducing NOx emissions, while overdosing of AdBlue could lead to ammonia emissions.

The issue of ensuring ongoing SCR performance in rail will apply not only to retrofit systems but also to newer rolling stock where functioning SCR is required to ensure compliance with Stage IIIB/V emission standards.

Onroad SCR installations include system messaging to warn of low AdBlue levels and ultimately can prevent a vehicle being operated until the issue is addressed. Rolling stock running out of AdBlue and so requiring removal from service would have significant implications for the railway. However, since SCR is not effective at idle (and so cannot address air quality issues at major stations), one of its primary purposes would be addressing onboard levels of NOx experienced by passengers while onboard the train. It is worth noting that recent onboard measurements of NOx do not show issues of concern for most rolling stock[16], and so a certain duration of SCR downtime before rectification of a problem in the depot could be acceptable. Further discussion with industry on the appropriate level of uptime and strategies for measuring downtime is therefore recommended before developing standards.

Specific future standards for SCR operation, could require that there will always be sufficient AdBlue available for expected operation. With future control of contracting of train operations passing to Great British Railways (GBR) there is the potential for this body to define common operating practices, possibly obviating the need for a standard to address this issue by coordinating with multiple parties. For instance, GBR could require that operators should use best endeavours to ensure that AdBlue tanks are filled up where practical. Other measures could be considered for earlier in the design and implementation phases, such as recommending that the effective "range" of AdBlue tanks be oversized compared to the fuel tank range. Best practice would then require that the Ad-Blue always be topped up during the time the vehicle is connected to the fuel pump and being refuelled. Such an approach would be easy to implement and track with standardised operating procedures.

For hybrid type options, battery performance will be crucial. There will be a risk of battery degradation overtime altering the extent and duration of regimes in which the engine is not running. Hence it will be necessary to monitor battery performance over time in service and to ensure timely replacement takes place. Oversizing of the battery specification has often been used to provide a suitable margin against degradation and will also decrease the rate of degradation.

11.3 Using audio analysis to fill specific data gaps

While the Testing Protocol provides suitable mode test points and weightings for existing configurations it will be necessary to determine what the future (post installation) equivalents will be. In some cases this can be derived from available component and OEM design data for the fluid coupling mode for DHMUs and for

[16] Green, D., A. Font, A. Tremper, M. Hedges, S. Lim and B. Bos (2021). *CLEAR: Analysis of Air Quality On Board Trains*. RSSB.

DMMUs in the mechanical fixed gear ratio parts of the mechanical transmissions. Audio analysis, as presented in this report, has confirmed that it is possible to accurately determine the rpm from the available design data (so further audio data collection is not necessary).

Audio data collection is recommended for targeted assessments, including understanding the range of engine rpm in each notch while in torque convertor mode, real idle conditions, transitions between torque convertor and fluid coupling modes in DHMUs, and transitions between torque convertor to lowest gear and between gears in DMMUs. Without this additional data from targeted assessments it will not be possible to fully delineate potential future drive cycle weightings since this data is not available from other sources in certain circumstances.