SUSTAINABLE DEVELOPMENT

A Better Safer Railway

CLEAR: Performance Requirements and Testing Protocols for Emissions Mitigations

Testing Protocol

T1235

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Published:

June 2022

Overview

The GB rail industry requires an understanding of the emissions arising from diesel engines, and how these vary with engine age, operation and different technologies. This document provides a Testing Protocol for assessing emissions in a consistent way so that results from different testing sessions can be compared and the most effective mitigation options can be understood.

To date, there has not been an agreed protocol to undertake rail emissions testing for in-vehicle installations and this has led to the use of different methodologies and, in some cases, unsatisfactory and inaccurate results. Furthermore, there is limited documentation in the public domain about how to conduct measurements and calculations relevant to rail engine emissions testing. This document therefore aims to consolidate the information needed to conduct reliable rail emissions testing, and to provide a rail emissions Testing Protocol. This will enable testing to be commissioned, planned and undertaken in a more informed and consistent manner and will lead to more accurate results that are comparable between testing sessions.

Normalised metrics are commonly used to quantify emissions, taking the form of emissions mass per activity data metric. Therefore, the relevant activity data must also be measured along with the data gathered through use of emissions monitoring equipment. Three core metrics used to quantify emissions are:

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

Total emissions can then be calculated by multiplication by a relevant quantifier, such as power, exhaust volume or time.

All testing approaches rely on an accurate understanding of either the mass or volume of selected inputs and outputs which need to balance. This balance then allows other outputs (emissions) to be calibrated to fuel or energy usage or to exhaust flows.

The air quality pollutants that should be measured are the following:

Gases:

- Nitrogen oxide
- Nitrogen dioxide
- Carbon monoxide
- Nitrous oxide
- Methane
- Total unburnt gaseous hydrocarbons

Particulates:

- Particulate mass
- Particulate number
- Bosch Smoke Number (as a good general measure of engine health rather than as a substitute for Particulate Mass (PM) or Particulate Number (PN))

The following should also be measured for post-processing calculations as part of testing:

- Carbon dioxide
- Residual oxygen

Diesel-electric transmission and diesel-hydraulic/mechanical transmission rolling stock require different testing procedures. The former can provide testing loads while the engine is installed on the rolling stock, but the latter cannot, usually necessitating the removal of the engine for testing.

Rail emissions testing requires testing emissions at a series of mode test points (particular combinations of engine speed (rpm) and power) that can then be weighted, based on the relative occurrence of those conditions in real-world use, to determine aggregated single metrics for a full drive cycle or to model emissions across a specific duty cycle.

A core aim of this Testing Protocol is to ensure testing is carried out at representative mode test points for the particular engine and installation case, therefore tailoring the testing to the specific situation. The associated Methodology Report (Grennan-Heaven et al., 2022) discusses the development of specific mode test points for different types of rolling stock, starting with the simplest diesel-electric transmission case and then proceeding to discuss the more complex diesel-hydraulic and diesel-mechanical cases. In the former case, emissions only need to be measured at a limited number of fixed power outputs. Whereas in the latter cases, because of the complexity of the transmission, the engine power output (and so the emissions) will vary with engine power setting, engine speed and train speed. Thus, for diesel hydraulic and diesel mechanical transmission rolling stock, the engine needs to be tested at multiple combinations of engine power, torques and speeds.

Recommended specific mode test points and drive cycle weightings for all of the rolling stock classes in scope for the Testing Protocol are provided in the associated spreadsheet.

Since the focus of this Testing Protocol is on evaluating real world conditions rather than those that form part of regulatory drive cycles, the mode test points recommended relate to real world usage settings. In a few cases the mode test points recommended here will be the same as regulatory mode test points but in most cases they will be different. Testing is split into two aspects: testing the average emissions at mode test points assuming stable running conditions; and testing where emissions are not stable over time such as a cold start or SCR after transitioning to an extended period of idle.

The sampling time used for emissions analysis for each mode test point should be a minimum of 5 minutes and preferably longer and should start once the engine has stabilised in a given mode.

Confidence in emissions testing results for each mode test point comes partially from repeatability of testing at each mode test point. Three complete repeats of testing in each mode test point would normally be considered sufficient in this regard to achieve 95% confidence levels.

The output from the testing and weightings when combined with further analysis of typical distances covered from on-train monitoring recorder (OTMR) data, could be used to convert results to "per km" or "per litre of fuel" values to provide a high-level context for operators.

Locomotive and DEMU engines

The locomotive and diesel electric multiple unit (DEMU) engine testing sequence is separated into two parts. Part 1 covers pre-testing and ends with a stop and review point where expectations for engine performance and emissions should be checked before then proceeding with the main testing sequence. Checks should include:

- Fuel consumption (is in line with expectations, see Spreadsheet 1 – Engine Settings, Drive Cycles and Test Results for values)
- Exhaust temperatures (are in line with expectations, see Spreadsheet 1 – Engine Settings, Drive Cycles and Test Results for values)
- For most calculation methods, that the carbon and oxygen balances are within required tolerances
- Measured gases and PM levels in the exhaust stream are in line with general expectations.

The pre-testing sequence should take less than 35 minutes in total.

Part 2 of the locomotive and DEMU engine testing sequence includes the core mode test points. The main testing sequence should take a maximum of 5 hours in total (assuming the engine takes a very long time to settle with stable conditions at each change) and can be realistically achieved within 3.5 hours.

DHMU/DMMU engines

The diesel hydraulic multiple unit (DHMU) and diesel mechanical multiple unit (DMMU) engine test modes and sequences for testing engines on dynamometers have both similarities and differences to the locomotive and DEMU (on-board) modes and sequences.

Similarities are:

- Pre-testing
- Dynamic scenarios (to evaluate engine start-up emissions and potential SCR effectiveness)
- Engine stabilisation requirements after changing mode.

Differences are:

- The requirement to specify notch, engine rpm and engine load (kW) rather than just notch for each mode test point
- Pre-testing includes an extra mode test point so both the highest and lowest specified rpm in the highest notch are included. A substantial difference in exhaust temperature and some gaseous emissions (e.g. nitrogen oxides, NOx) is expected between the highest and lowest specified rpm in the highest notch.
- Shorter sampling average time, 3 minutes instead of 5 minutes at each mode test point
- The main testing sequence starts at maximum power and rpm, e.g. Notch 7 at maximum rpm, then for the next step in the testing sequence the engine rpm decreases. Reducing (rather than increasing) the engine rpm and applied dynamometer load for the majority of changes minimises the time taken for the engine to stabilise, thus helping to minimise overall testing time. After testing at the lowest engine rpm in each notch, the next step in the sequence is to change to the maximum rpm in the next lowest notch.
- The repeat of the mode test points is achieved by repeating the whole main test sequence rather than stepping down the pyramid as for the locomotive testing.

Confidence in the testing results is achieved despite shorter average sampling times (than for locomotive testing) with the combination of two repeats of the main testing sequence and a significantly larger number of mode test points which give more confidence in the robustness of the data from the adjacent test points.

Reading guide

This section outlines the structure of this document and where to find particular information, guidance and requirements. The general flow of the document first covers consideration of the purposes of the particular desired emissions testing and the consequent implications and constraints for the testing approach, then preparing for testing, conducting testing and finally calculating and documenting the testing results.

Section 2 provides relevant background, including an overview of emissions measurements (more detail is provided in the associated Methodology Report), the mass or volumetric balance approaches to testing, and challenges for rail compared to other sectors for field-based testing.

Section 3 covers general considerations, including whether testing can be conducted on or off the vehicle, and defining the purpose of testing to be performed in each individual case, which is a key question that should be fully understood before embarking on testing. Understanding beforehand the mode test points and drive cycles to be tested, as well as whether these might change after a mitigation solution has been installed, is critically important. Environmental effects (i.e. ambient conditions) can impact test results and the timing of field-based testing is thus potentially important.

Section 4 discusses selecting a specific balance approach which will be dictated by the ability to measure fuel flow and/or exhaust flow accurately. Section 5 describes the required equipment and instrumentation.

Section 6 covers multiple aspects of setting-up the testing. Investigation of the range of parameters and expected values should be made prior to set up. The section covers the core aspects of which mode test points emissions should be measured at, for how long the engine should be run in those conditions, and in what sequence. The number and sequence for locomotives/DEMUs is substantially simpler than for DHMU/DMMUs. Pertinent aspects that should be considered include fuel testing, positioning sampling equipment, and engine control during testing.

Section 7 discusses the accuracy and precision of the required parameters (in addition to emissions concentrations) that should be measured while conducting testing.

A detailed step-by-step guide to performing calculations to derive mass-based emissions estimates is given in Section 8. The required results documentation is described in Section 9 as well as in the associated Spreadsheet 2 (Emissions Calculations Template) which contains each of the steps and equations in Section 8.

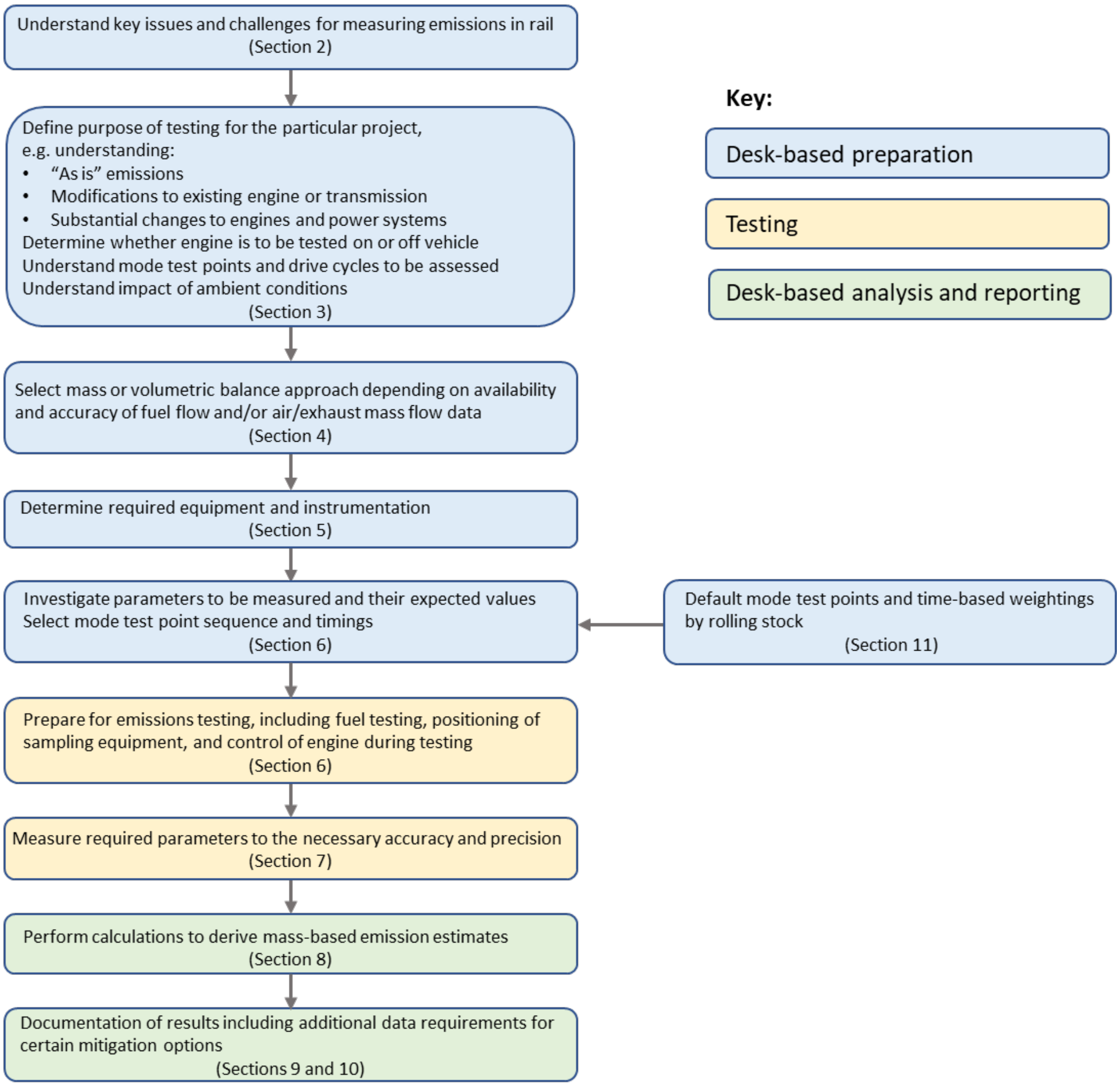
Section 10 discusses the additional data requirements for certain mitigation options that will be necessary to ensure solutions are effective in real-world conditions. These should be documented in the associated Spreadsheet 3 (Additional Data Requirements).

Default mode test points and total time-based weightings to replicate real-word drive cycles are summarized in Section 11 and values are provided in the associated Spreadsheet 1 (Engine Settings, Drive Cycles and Test Results) for each rolling stock type in scope.

A list of the specific references cited in this document, a bibliography of sources that were used to develop the Testing Protocol, and relevant definitions, terms and constants are provided at the end of this document.

A flowchart outlining the steps in the Testing Protocol is presented in Figure O-1.

Figure O-1 Testing Protocol flowchart



Abbreviations

AFR	Air:fuel ratio
CARB	California Air Resources Board
CEN	European Committee for Standardisation
CFR	Code of Federal Regulations
CLEAR	Clean Air Research Programme
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CPC	Condensation particle counter
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
EPA	Environmental Protection Agency
ETS	Electric train supply
FAME	Fatty acid methyl ester
FID	Flame ionisation detector
HC	Hydrocarbon
IR	Infrared
ISO	International Standards Organisation
LNG	Liquified Natural Gas
NDIR	Non-dispersive infrared
NMHC	Non-methane hydrocarbons
NO	Nitric oxide
NO_2	Nitrogen dioxide
NOx	Nitrogen oxides
NRMM	Non-road mobile machinery
OBD	On-board diagnostics
OTMR	On-train monitoring recorder
PAH	Polycyclic aromatic hydrocarbons
PEMS	Portable emissions measurement systems
PM	Particulate matter

PN	Particle Number
RCM	Remote conditioning monitoring
RH	Relative humidity
SAE	Society of Automotive Engineers
SCR	Selective catalytic reduction
SF_6	Sulphur hexafluoride
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

The GB rail industry recognises the need for an improved understanding of the emissions from rail diesel engines, how these vary with engine age and operation, and how effective mitigation measures can be developed (GB Rail Industry, 2020). Measurement of emissions can help in this regard but there are several challenges when measuring emissions from rail engines installed in a vehicle compared to other sectors such as road. For example, rail engines may have more inaccessible exhaust systems and the quantity of exhaust gases is much higher. Consequently, the core aim of the T1235 project was to therefore provide guidance and a Testing Protocol for objectively and consistently assessing and comparing realistic mitigation options for their real-world benefits and limitations.

This document is aimed at two key groups. The first is decision makers in the rail industry who need to either (a) approve funding for emissions testing or (b) obtain an understanding of the emissions testing carried out and the robustness of the results in conclusions. This document is intended to aid in the making of defensible investment decisions regarding the effectiveness of mitigation solutions in key rail environments. The second group is technical staff involved in any part of an emissions testing programme or upgrade programme. This may include rail engineering staff, as well as emissions testing staff who may not be familiar with the particular challenges of emissions testing for rail.

To date, there has not been an agreed protocol to undertake rail emissions testing for in-vehicle installations and this has led to the use of different methodologies and, in some cases, unsatisfactory and inaccurate results. Furthermore, there is limited documentation in the public domain in general about how to conduct measurements and calculations relevant to rail engine emissions testing. This document therefore aims to consolidate the information needed to conduct reliable rail emissions testing, and to provide a rail emissions Testing Protocol. This will enable testing to be commissioned, planned and undertaken in a more informed and consistent manner and will lead to more accurate and comparable results.

In the regulatory context, GB rail diesel engines are considered as part of the non-road mobile machinery (NRMM) category. In Europe, the regulation of NRMM is largely covered by International Standards Organisation (ISO) standards. In the US there are rail specific testing standards. These have some commonality both with other US NRMM testing and with the ISO-based NRMM testing but there are also marked differences between the European/ISO-based approach and US approaches. The European/ISO-based approach is focused on producing a single drive cycle specific number for each pollutant, while obfuscating the detail and not using real engine running conditions for testing. The US approach aims to produce a representative single drive cycle specific number, based on the detail from different real engine running conditions and drive cycles (e.g. US EPA, 1998, 2009).

There have also been a number of research studies, both in the UK and overseas, investigating different methodologies for the testing of in-service rail diesel engines. Many useful lessons can be learnt from the US approach and the previous research studies (e.g. Fritz and Starr, 1993; US EPA, 1998, 2009; Southern Research Institute, 2005; ABMARC, 2016). The aim of this Testing Protocol is to maximise the useful and transferrable knowledge from that previous work for use in future in-service rail diesel engine emissions testing and to enable more accurate and consistent testing to be undertaken.

This Testing Protocol provides a repeatable representation of the common duty cycles for each major rolling stock class that has the potential to be retrofittted with emissions mitigation solutions. It is intended to provide a cost effective, practical and straight forward method to benchmark the performance of retrofit mitigation options across diesel rolling stock types in real world use. This is done by providing practical advice on how to prepare for and then carry out emissions testing, to record results, and to accurately calculate mass-based emissions, which will enable the development of transparent and transferrable conclusions.

As an extension to the T1187 project *CLEAR: Fleet wide assessment of rail emissions factors*, RSSB commissioned the development of a protocol focused on methods to calculate mass-based emissions from emissions testing data (Grennan-Heaven and Gibbs, 2021) which has served as the foundation for this Testing Protocol. That work was extended here in the T1235 project to include further information and requirements for testing approaches and calculation methods and to provide recommended mode test points for the relevant classes in the GB diesel rolling stock fleet.

This protocol is based upon relevant material in ISO Standard 8718 and the US Code of Federal Regulations (CFR), United Nations Economic Commission for Europe (UNECE) R49, and World Harmonised Stationary Cycle (WHSC) and World Harmonised Transient Cycle (WHTC) development, which has then been adapted to suit the needs of the GB rail industry. Relevant background material and key considerations for rail emissions testing, the approach followed here, and the development of the protocol is provided in the associated Methodology Report for this project (Grennan-Heaven at al., 2022).

The remainder of this document is structured as follows. Section 2 provides an overview of emissions measurements, approaches to testing and differences between regulatory and real-word emissions testing. Sections 3, 4, 5 and 6 address preparing for testing, covering general considerations, selecting an approach, the required facilities and equipment, and set up, respectively. Section 7 discusses the accuracy and precision of the required parameters (in addition to emissions concentrations) that should be measured while conducting testing. A detailed step-by-step guide to performing calculations to derive mass-based emissions estimates is given in Section 8. The required documentation is described in Section 9 as well as in an associated calculations template spreadsheet. Section 10 discusses additional data requirements for specific mitigation options. Default mode test points and total time-based weightings to replicate real-word drive cycles are summarized in Section 11 and provided in the associated spreadsheet for each rolling stock type in scope. The remaining sections contain specific references, a bibliography and relevant definitions, terms and constants.

2 Background

2.1 Key concepts of emissions measurements

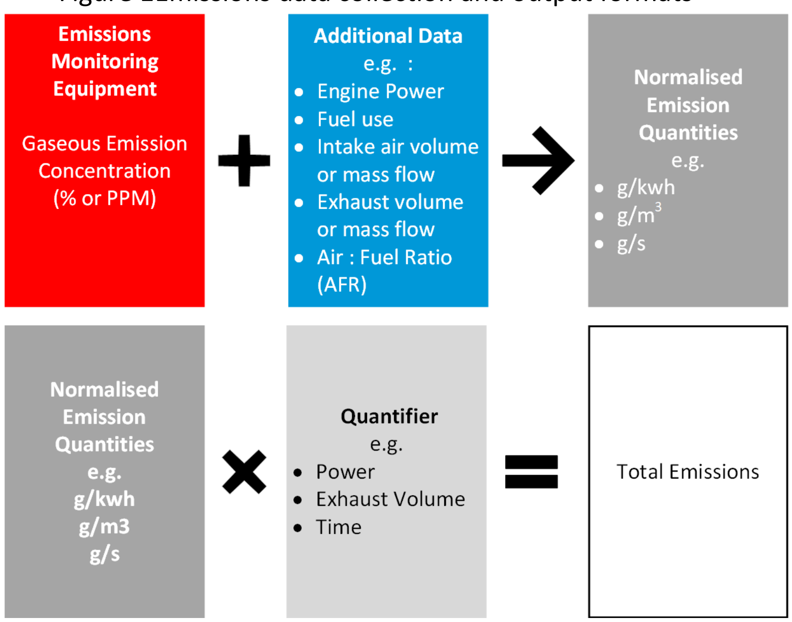
The main emissions from engines are generated during the combustion of fuel and engine oil. Additionally, some emissions are also produced in the engine exhaust, or through chemical reactions due to high in-cylinder temperature and pressure.

Normalised metrics are commonly used to quantify emissions, taking the form of emissions mass per activity data metric. Therefore, the relevant activity data must also be measured along with the data gathered through use of emissions monitoring equipment. Three core metrics used to quantify emissions are:

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

Total emissions can then be calculated through multiplication by a relevant quantifier, such as power, exhaust volume, or time as demonstrated in Figure 1.

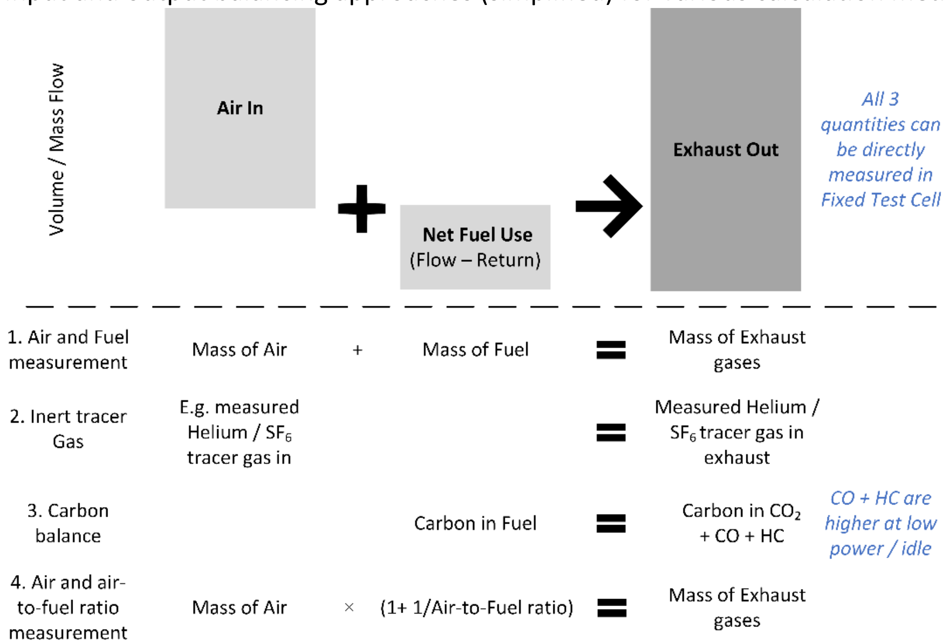
Figure 1Emissions data collection and output formats



2.2 Testing approaches

All testing approaches rely on an accurate understanding of either the mass or volume of selected inputs and outputs which need to balance (see Figure 2). This balance then allows other outputs (emissions) to be calibrated to fuel or energy usage or to exhaust flows.

Figure 2Input and output balancing approaches (simplified) for various calculation methods



2.2.1 Balance approaches for static/fixed testing

Traditionally emissions testing for road vehicles was exclusively conducted in static / fixed test cells with the engine mounted on a dynamometer. This provides controlled and measured loads at different engine speeds. This approach could be followed for rail engines but would need some detailed work to accurately assess real world loads and duty cycles for the dynamometer to apply. In static test cells, both the emissions concentration and additional data such as the exhaust volume or mass flow can easily be collected. A static/fixed test cell approach involves two parallel strands to maximise accuracy of the testing and calculations.

In the first strand the following are measured:

- For the air entering the engine - volume, mass, pressure, humidity, density and temperature related to the intake air mass flow.
- The fuel mass flow, i.e. the net fuel use, the difference in fuel going to the engine and that being returned to the tank. (For rail engines the fuel used in the engine is between 5% and 50% of that taken from the tank, the rest being returned at a higher temperature and hence different density than when it left the tank, thus making accurate measurement difficult.)
- For the exhaust flow leaving the engine - volume, mass, pressure, density and temperature. These are measured or part calculated.

If the overall accuracy of measurements is sufficiently high and the most accurate calculation methodology is used, then often only two of the mass-flow measurements (typically the intake air mass flow and fuel mass flow) need to be recorded to produce accurate and repeatable results.

In the second strand, the quantities of various chemical elements entering and leaving the engine are compared and should balance. This allows the amount of fuel, oxygen consumption and carbon dioxide (CO_2) production to be accurately calculated. The engine CO_2 production is 2-4 orders of magnitude higher than for other combustion emissions, hence the importance of accurately calculating and calibrating CO_2 first.

With field-based testing (i.e. non-static test-cell testing) it is very difficult to measure the air intake volume / mass flow in practice, hence without this measurement far more fuel consumption data is required (and potentially exhaust mass flow is also required if the absolute highest accuracy in fuel flow cannot be achieved).

2.2.2 Field-based testing

Field-based testing is the regulatory term for installed engine testing, i.e. testing not taking place in a static test-cell. In recent years, the size and mass of emissions testing equipment has reduced substantially. This smaller, lighter and less power-hungry equipment has been given the term portable emission measurement systems (PEMS). However, PEMS only addresses the first set of measurement requirements (emissions concentration). Parameters such as the engine power, fuel use and air / exhaust gas volume or mass, and atmospheric conditions need to be measured via other methods. The automotive sector has been able to address this information gap for newer vehicles with pre-existing data streams from the engine or the use of direct measurement of exhaust mass flow which is not feasible in larger rail engines, hence the comparatively quick adoption of PEMS in that sector and its required use for certification testing. Modern road vehicles have computer-controlled engines combined with the mandatory fitting of on-board diagnostics (OBD-II) or CANbus ports (with open data standards) to motor vehicles to allow live data communication, export and diagnostics. The additional data needed to accurately quantify the mass of emissions can therefore often be collected without any additional measuring equipment being used. However, there are some potential caveats around data accuracy as it relies on accurate values for fuel flow for given fuel injector parameters and both the fuel and fuel injectors being in an identical (i.e. fuel temperature and viscosity being the same and injectors in “new” not “worn” or drifted state) condition to those used when calibrating the parameters.

Using PEMS to measure quantities of emission from non-road mobile machinery (NRMM) engines such as rail has additional challenges compared to the automotive sector:

- Older engines do not have engine computers and therefore have none of the potentially useful data streams generated by such computers.
- Where fitted, (non-road vehicle) engine control unit (ECU) computers do not have open standards for external connections or open data encoding and formatting, so it is more challenging to acquire the data. Secondly, the data cannot be automatically processed and aligned by PEMS computer systems, thus requiring much more post processing.

- The larger size of rail engines requires greater fuel and air use and levels of turbo charging and therefore the accuracy of fuel use and exhaust volume / mass flow measurements has a greater impact on the overall calculation accuracy than for road vehicles.
- The air intake and filter geometry on rail rolling stock make it very difficult to accurately measure air mass flow.
- PEMS units are typically designed for on-road vehicle engine testing, where in many cases the exhaust temperatures, pressures and volumes are much lower than for rail engines. Smaller rail diesel multiple unit (DMU) engines are approximately the equivalent of medium-high power heavy goods vehicle engines, hence the smallest rail engines align with the higher power road engines. (For example, the rail engines in use in Great Britain have exhausts that range from 5” to 14” (127 – 356 mm) in diameter, larger than the on-road size range which goes up to 5".) Therefore, PEMS equipment is unlikely to be effectively used without careful thought or investigation.

2.3 Regulatory emissions testing versus real-world emissions testing

Regulatory emissions testing aims to produce comparable testing under identical standardised conditions. This document is not focused on regulatory testing and all associated requirements. Rather, it is focused on real-world testing that will be far more useful for the GB rail industry’s understanding of emissions and on real world engine settings, conditions and emissions, while maintaining as much comparability between studies as possible.

3 Preparing for testing – general considerations

3.1 Emissions to be measured and requirements

The pollutants that should be measured are these:

Gases:

- Nitrogen oxide
- Nitrogen dioxide
- Carbon monoxide
- Nitrous oxide
- Methane
- Total unburnt gaseous hydrocarbons

Particulates:

- Particulate mass
- Particulate number

The following should also be measured for post-processing calculations as part of testing:

- Carbon dioxide
- Residual oxygen

3.2 Rolling stock testing options

Diesel-electric transmission and diesel-hydraulic / mechanical transmission rolling stock require different testing procedures. The former can provide testing loads while the engine is installed on the rolling stock but the latter cannot, usually necessitating the removal of the engine for testing.

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

3.3 Defining the purpose of testing

The purpose of the emissions testing needs to be clearly understood by all those involved, including sponsors, in order to produce successful outcomes. The three main potential reasons for testing are:

- An accurate picture of the current emissions at a single point in engine usage to inform potential thinking around emissions mitigation options
- An accurate picture of how the emissions increase over time with usage
- Assessing the effects of implementing an emission mitigation option by a direct before and after comparison.

In many cases ignoring the first two reasons can lead to a poor understanding when designing mitigation options and their efficacy in real-world operating conditions.

Sufficiently detailed testing allows evaluation of three key settings in rail:

- The total drive cycle, which includes all engine usage both in and out of service and when undergoing maintenance activities
- Stations (predominantly idle)
- In-service and representative of passenger exposure (sustained running at higher engine powers, as well as an idle component representing coasting / braking (typically circa 20-25% of total drive cycle) and dwell times mostly in intermediate stations although this is smaller than that in the total drive cycle proportion of idle).

While a lot can be achieved from using the mode test point data under standardised conditions, evaluating certain aspects of engine usage and emissions requires specific scenarios, for example, decline in selective catalytic reduction (SCR) performance as exhaust temperatures decline.

An understanding of the testing purpose then dictates the detailed requirements for testing.

3.4 Understanding the mode test points and drive cycles

Rail emissions testing requires testing emissions at a series of mode test points (particular combinations of engine speed (rpm) and power) that can then be weighted, based on the relative occurrence of those conditions in real-world use, to determine aggregated single metrics for a full drive cycle or to model emissions across a specific duty cycle.

A core aim of this Testing Protocol is to ensure testing is carried out at representative mode test points for the particular engine and installation case, i.e. tailored to the specific situation. The associated Methodology Report (Grennan-Heaven et al., 2022) discusses the development of specific mode test points for different types of rolling stock, starting with the simplest diesel-electric transmission case and then proceeding to discuss the more complex diesel-hydraulic and diesel-mechanical cases. In the former case, emissions only need to be measured at a limited number of fixed power outputs. Whereas in the latter cases, because of the complexity of the transmission, the engine power output (and so the emissions) will vary with engine power setting, engine speed and train speed. Thus for diesel hydraulic and diesel mechanical transmission rolling stock, the engine needs to be tested at multiple combinations of engine power, torques and speeds.

Recommended specific mode test points and drive cycle weightings for all of the rolling stock classes in scope for the Testing Protocol are provided in the associated Spreadsheet 1 – Engine Settings, Drive Cycles and Test Results. Required sampling times at each mode test point and the sequencing of mode test points are discussed further below in Section 6.2 of this document. Adapting mode test points and drive cycles to reflect changes post installation of a mitigation option is described in Section 9 of the associated Methodology Report.

3.5 Understanding the impact of proposed mitigation solutions on testing requirements

Many potential mitigation solutions will result in changes to the drive cycle weighting and/or the mode test points as the engine may now be operating in a different regime. The testing must therefore account for this to ensure the actual reductions in emissions are fully understood.

At an early stage it will be necessary to accurately identify the likely changes to the mode test points so that the necessary data can be gathered as part of the emissions testing. While it would also be useful to have a prior understanding of changes to the drive cycle weightings, this is not necessary to know prior to emissions testing as this weighting can be adjusted in calculations post testing.

3.6 Considering environmental effects

The quantities of emission products from combustion vary with ambient temperature, atmospheric pressure and in the case of nitrogen oxides, relative humidity. These variables can significantly impact emission testing results. Therefore, regulatory emissions testing values are standardised against standard temperature, pressure and humidity with set "correction" (normalisation) calculation methods to adjust the raw test value under the test conditions to standard conditions.

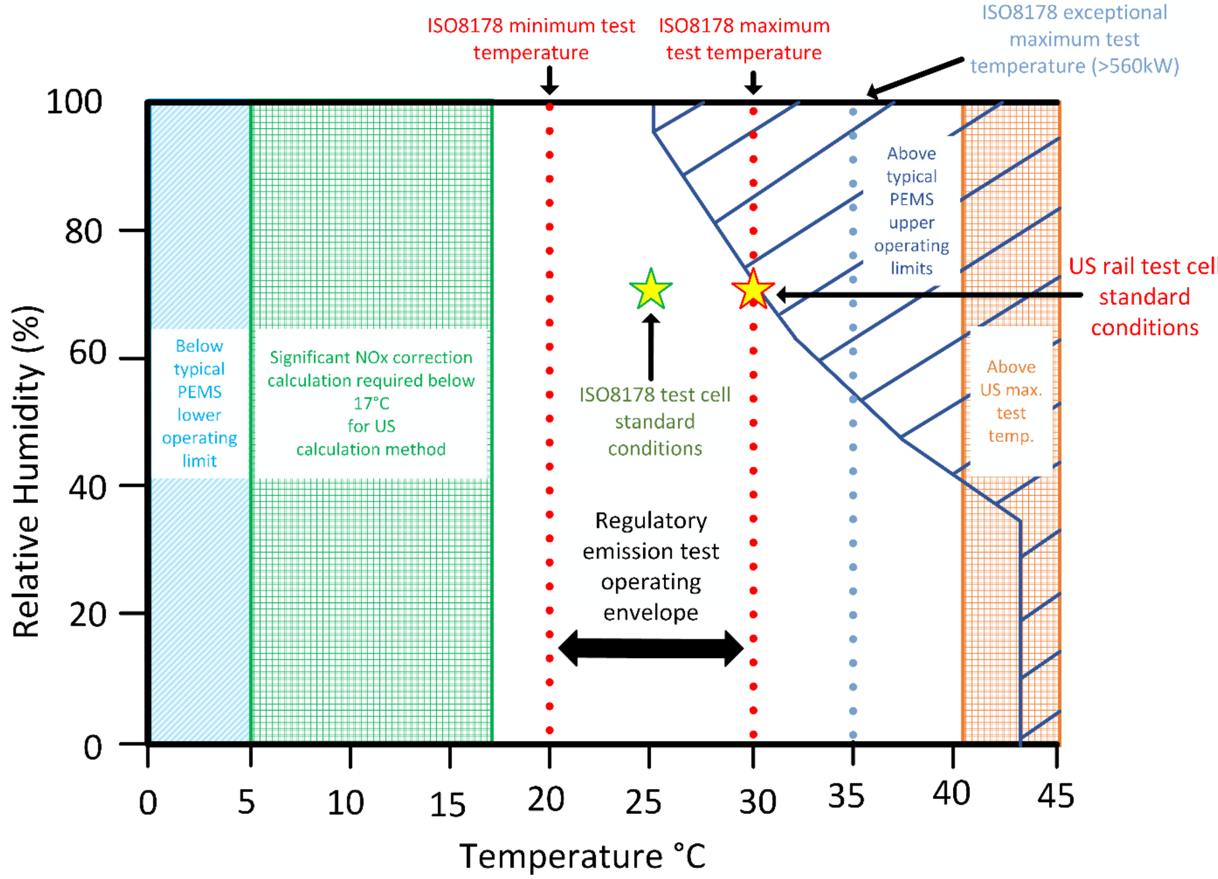
Apart from stationary idle testing, DMU engine testing is typically conducted on dynamometers where environmental conditions are more constant and nearer standard conditions. On-site on rolling stock testing will be outside under more variable conditions so potential variations versus standard conditions will be much larger.

The temperature and humidity in test cell conditions are generally constant during a year and standard test conditions are set at 25°C and 71.8% relative humidity with only relatively small permitted deviations. Care must therefore be taken when scheduling testing in open air, and corrections to calculations should be performed in accordance with ISO 8178:4 calculation methodology.

However, the scale of corrections applied under some open-air testing conditions (e.g. extremes in summer or winter) are far larger than under regulatory testing conditions. Such corrections are discussed below in Section 8 (Post Testing – Performing Calculations).

The correction calculations are an attempt at correction and are not entirely perfect with different correction calculations for different test standards. For example, using the ISO 8178:4 calculation methodology, a 5°C difference and 10% difference in relative humidity from the standard conditions result in measured nitrogen oxides (NOx) levels needing to be corrected by 2.4%. If the testing was conducted in winter at 5°C ambient temperature (the lower limit for most PEMS equipment) then the correction factor needed would be 8.4%. For comparison, the US calculation methodology correction factors are even larger. For example, in field engine tests the total accuracy limit for the test and calculations is ≤9.0% with accurate data collection and correction for non-standard conditions potentially having a large effect. Given the uncertainty in large corrections, ISO 8178:2 lays down strict air temperature conditions for field-based tests of 20-30°C (exceptionally up to 35°C for larger engines) to minimise this uncertainty for regulatory compliance. Similarly, the US approach advises against testing below 17°C but does still permit it, albeit with significant temperature correction factors to ensure lower emission levels cannot be used for regulatory compliance by testing in cooler conditions. The various temperature and humidity constraints on testing are shown in Figure 3.

Figure 3 Environmental condition ranges for regulatory engine emissions testing



4 Preparing for testing – selecting an approach

The internationally approved approaches to emissions measurement (e.g. UNECE R49, ISO 8178 and all CFR approaches) are all mass or volume balance-based to some extent i.e. the quantity of a particular chemical element entering and leaving the engine has to be equal though its molecular form may change. Assessment of the relevant literature shows that there are four key measurement methods that are applicable in some form to rail engine exhaust emissions (Figure 2). These are:

- Air and fuel measurement
- Tracer measurement
- Fuel flow and chemical balance measurement
- Air and air-to-fuel ratio measurement

Calculating gaseous emissions from emission concentration measurements can be conducted by either a mass-based approach in or a molar-based approach; the more common mass-based approach is outlined in this document. The processes and options outlined below have been developed using the relevant ISO 8178-1, -2 & -4 and US CFR emissions testing and calculation methodologies that are applicable to rail diesel engines.

The gaseous exhaust components emitted by the engine can be measured on either a raw or dilute exhaust gas basis, however if measured on a dilute basis without intake or exhaust mass flow measurements, the accuracy of the calculations will be lower.

Particulate emissions have traditionally been measured by the gravimetric filter method with diluted rather than raw exhaust gas. The move to continuous second-by-second sampling has led to several measurement techniques being developed most of which continue to use dilution of the exhaust gas stream. A small number of newer techniques (mainly for research and development rather than regulatory use so far) allow undiluted measurement of particulate matter (PM) in the raw exhaust stream.

If the emissions testing is being conducted with field-based engine testing while on rolling stock it is unlikely that air intake or exhaust mass flow measurements can be collected, limiting the potential calculation options.

For exhaust emission calculation i.e. converting the measured concentrations to mass-based metrics, the total exhaust mass flow needs to be determined and there are several potential methods (as outlined below) that can be used depending on what is measured or what can be measured.

The key equation the underlying all the metrics is the mass flow balance:

$$Mass\ flow\ out = Mass\ flow\ in$$

$$q_{\mathrm{mew},i} = q_{\mathrm{maw},i} + q_{\mathrm{mf},i} \quad (1)$$

where:

q_{maw} = Intake air mass flow rate on wet basis [kg/s]

q_{mew} = Exhaust gas mass flow rate on wet basis [kg/s]

q_{mf} = Fuel mass flow rate [kg/s].

The four calculation methods are outlined in brief below with the calculation details covered fully in Section 8: Post Testing – Performing Calculations.

4.1 Method 1 – Air and fuel measurement

The air and fuel measurement method—measuring q_{maw} and q_{mf} to allow calculation of q_{mew} (see ISO 8178-1:2020, 6.4.4.1 and ISO 8178-4:2020 9.1.2.1) is most likely to be used with dynamometer-based testing where the intake air mass flow rate and fuel mass flow rate can be easily measured (both quantities on the right-hand side of Equation (1) are measured), allowing a very simple calculation of the total exhaust mass flow.

Method 1 is the default choice for laboratory-based measurements or field-based testing of newer vehicles where the vehicles have accessible in-built data streams for air and fuel flow (e.g. via OBD-II port or CANbus). This method is not suitable for field-based rail emissions testing.

4.2 Method 2 – Tracer measurement

The tracer measurement method (see ISO 8178-1:2020 Section 6.4.4.3 and ISO 8178-4:2020 Section 9.1.2.2) involves measurement of the concentration of an inert tracer gas such as helium or sulphur hexafluoride in the exhaust. This concentration is compared to the quantity of tracer gas injected into the intake air (always in a negligible quantity so combustion and hence the emissions calculations are not affected). The calculation of the instantaneous exhaust gas flow $q_{mew,i}$ [kg/s] is made as follows:

$$q_{mew,i} = \frac{q_{Vt} \times \rho_e}{10^{-6} \times (c_{mix,i} - c_b)} \qquad (2)$$

where:

q_{Vt} = tracer gas flow rate [m^3/s]

$c_{mix,i}$ = instantaneous concentration of the tracer gas after mixing [µmol/mol]

ρ_e = density of the raw exhaust gas [kg/m^3]

c_b = background concentration of the tracer gas in the intake air [µmol/mol].

The background concentration of the tracer gas c_b can be determined by averaging the background concentration measured immediately before the test run and after the test run. When the background concentration of the gas used as the tracer is less than 1% of the concentration of the tracer gas measured after mixing $c_{mix,i}$ at maximum exhaust flow, the background concentration may be neglected.

Method 2 can potentially be used when it is difficult to collect certain data items or use other calculation methods (e.g. for dual fuel engines in field-based testing). It has been very rarely used but is now gaining popularity for field based on-road engine testing.

4.3 Method 3 – Fuel flow and chemical balance measurement

The fuel flow and carbon and oxygen balance measurement method (see ISO 8178-1:2020 Section 6.4.4.3 and ISO 8178-4:2020 Appendix D.3.2.3.1) is the default choice for field-based measurements where measuring the intake air or exhaust mass flows is difficult or impossible but fuel mass flow rates and fuel compositions are known very accurately. The slightly less accurate oxygen balance calculation method serves as a useful accuracy check for the carbon balance method.

Method 3 is highly suitable for field-based testing of locomotives or multiple units with electric transmission.

4.4 Method 4 – Air and air-to-fuel ratio measurement

The air and air-to-fuel ratio measurement method (see ISO 8178-1:2020 Section 6.4.4.4 and ISO 8178-4:2020 Section 9.1.2.3) is used where the intake air mass flow rate and fuel chemistry can be easily measured and the stoichiometric air to fuel ratio and excess air ratio are used to estimate fuel flow.

$$q_{mew,i} = q_{maw,i} \times \left(1 + \frac{1}{A/F_{\mathrm{st}} \times \lambda_i}\right) \quad (3)$$

Method 4 is a potential choice where fuel flow data is not available but accurate intake air flow and fuel chemistry data are available.

4.5 Comparison of calculation methods and data requirements

The calculation methods 1-4 outlined above have different requirements for data items that need to be measured. Some of the data items are harder to measure than others particularly for field-based testing. Table 2 shows the four potential calculation methods and their data requirements.

Table 2 Data requirements for balance-based emissions measurement methods

Method	Exhaust gas concentrations	Air flow	Inlet air gas concentrations	Fuel flow	Fuel chemistry	Exhaust gas properties	Exhaust gas flow	Exhaust O_2 concentration
1. Air and fuel measurement	Yes	Yes	-	Yes	Yes	-	-	Yes
2. Tracer measurement	Yes	-	Yes	-	-	Yes	-	-
3. Fuel flow and carbon / oxygen balance measurement	Yes	-	-	Yes - with very high accuracy	Yes	No - potentially required if fuel flow accuracy is not high enough		Yes
4. Air and air -to-fuel ratio measurement	Yes	Yes	-	-	Yes	-	-	Yes

5 Preparing for testing – required facilities and equipment

5.1 Requirements for measuring gaseous emissions

The analytical measuring equipment and the methods for measuring gaseous emissions are described in ISO 8178-1:2020 7.3. For field measurements, the non-methane hydrocarbon analysis according to ISO 8178-1:2020, 7.3.5, is not applicable in most cases, as this method needs laboratory equipment (e.g. gas chromatographic equipment). For the measurement of non-methane hydrocarbons, the hydrocarbon cutter method of ISO 8178-1:2006 Section 7.3.5., should preferably be applied upstream of the heated flame ionisation detector (FID).

5.2 Requirements for measuring particulate emissions

The determination of particulates and the equipment needed should be as specified in ISO 8178-1:2020, chapter 8. However, the reference filter weighing time may be exceeded but should still be minimised as much as possible.

Field particulate sampling systems are not required to achieve the filter face velocity criteria required for laboratory systems in ISO 8178-1 and ISO 8178-11. The average filter face velocity should be calculated and declared with the test results. However, the 25 kPa maximum pressure differential increase should still be observed.

Particulate emissions have traditionally been measured by the gravimetric filter method with diluted rather than raw exhaust gas and most continuous measurement techniques continue to use dilution. For reasons of practicability, partial flow dilution systems are recommended for at site and field measurements. The move to continuous second-by-second sampling has led to several new measurement techniques being developed, some of which continue to use dilution of the exhaust gas stream. A small number of newer techniques (mainly for research and development rather than regulatory use so far) enable undiluted measurement of PM in the raw exhaust stream.

The weighing chamber conditions according to ISO 8178-1:2006 Section 7.6.3 also apply to the measurement at site and under field conditions. In cases where the weighing chamber is not located near the measurement site, it should be ensured that the loading of the filter does not change during the transport to the weighing chamber (see also 11.1 of this part of ISO 8178).

5.3 Emissions instrumentation

There is a range of different types of instrumentation available to measure emissions of the relevant air quality pollutants and greenhouse gases listed above in Section 3.1. This section is intended to provide an understanding of how this instrumentation works, how emissions are measured, and the key limitations.

5.3.1 Portable emissions measurement system

There are separate specifications for portable emissions measurement system (PEMS) instrumentation, such as accuracy and repeatability requirements (that are mostly aligned between Europe and the US), that are less strict than for laboratory-based emissions testing. For example, less strict requirements in Europe (ISO 8178:1), and in the US (40 CFR 1065 Subpart C), as well as lower requirements for in-field testing requirements (e.g. Europe in ISO 8178:2, US in 40 CFR 1065 Subpart J). In reality, most modern PEMS equipment meets and usually exceeds the stricter laboratory standards unless it has been designed to be ultra-compact as the primary design concern. Modern (non ultra compact) PEMS equipment items are now often used for laboratory testing.

5.3.2 Gaseous PEMS

Gas analysers provide second-by-second concentration data for the gases being measured. All analysers are mounted inside temperature-controlled enclosures to ensure stable conditions and a high accuracy. Exhaust gas flows through the 191°C temperature-controlled sample line to the analysers. This prevents unaccountable losses of hydrocarbon (HC) compounds and NO_2 through condensation forming in the sample line. Span (calibration) gases are used for calibration to ensure repeatability across all the gaseous emissions. Both US and ISO standards recommend testing well mixed raw exhaust gas flow without dilution, due to the reduced accuracy in field-based testing if air mass flow or exhaust mass flow are not accurately measured.

5.3.2.1 Non-dispersive infrared (NDIR) for CO and CO_2

Carbon monoxide (CO) and carbon dioxide (CO_2) measurements are conducted using non-dispersive infrared (NDIR) spectrometry optimised for high accuracy and resolution of CO at low concentrations. This technique is also sometimes used for the measurement of NOx and HC.

5.3.2.2 Ultraviolet (UV) for NOx

The measurement of nitric oxide (NO) and nitrogen dioxide (NO_2) can be conducted simultaneously and directly using an ultraviolet (UV) analyser (without the need of a NO_2 to NO converter that older techniques and equipment required). The UV analyser contains two specific frequency UV photometers measuring NO and NO_2 separately, which are then combined to provide NOx readings. Adding a third specific frequency photometer can allow the measurement of N_2O.

5.3.2.3 Heated flame ionisation detector (FID) for THC

PEMS normally uses a Heated Flame Ionisation Detector analyser for the measurement of total hydrocarbon (THC) concentrations. The flame ionization detector measures hydrocarbons by the ionization of carbon atoms in organic compounds when burned in a hydrogen flame. This generates an ionization current between two electrodes that is directly proportional to the number of organically bound carbon atoms present within the sample gas. This ionization current is amplified electrically and converted into a voltage signal that is calibrated to provide the level of THC.

5.3.3 Particulate PEMS

Particulate matter is always measured after the dilution of the engine exhaust and at a lower temperature then the gaseous emissions. There are many different dilution methods in practice, hence PM measurements and calculations are different from gaseous ones and can be more challenging.

5.3.3.1 Particulate dilution cell and transfer line

The dilution and exhaust transfer unit consists of the dilution cell connected to the sample probe, which receives a clean filtered dilution air supply. The dilution cell feeds directly into the 52°C heated transfer tube connected analyser. Either fixed or variable (proportionate) dilution ratios can be used. The US rail emission testing standard recommends a fixed dilution ration of 3.6 but it can be quite difficult to source an analyser that will cope with a ratio that low and dilution ratios of over 10 have been used to attempt to utilise available equipment but with considerable reductions in test accuracy. The temperature used is a compromise, maximising the mass of PM that cools, condenses into a solid and hence is measured as PM, whilst at the same time aiming to minimise water condensation.

5.3.3.2 Gravimetric filter module

The gravimetric filter module draws the diluted exhaust gas from the dilution cell, mounted just after the sample probe, through a PM filter. Traditionally this filter remained in-situ for the whole test providing a single whole test cycle PM emissions value. Occasionally and mainly in the US, individual testing mode (e.g. notch in the rail case) PM filter tests were conducted. A minimum filter capture efficiency of 99.995% is specified for filter elements.

In both Europe and the US there has been the desire to move to more accurate second-by-second PM emissions data for the current generation of emission standards for both road engines (e.g. Euro 6/VI Road) and non-road engines (e.g. NRMM Euro IIIB/V for rail), especially as newer engines produce less particulates and the measurement errors for filter-based methods become more significant at low quantities. Therefore, PM PEMS now provides time resolved (second-by-second) PM emissions data measurement in real time in parallel with the existing gravimetric filter PM mass. There are several techniques used for measuring time-resolved PM emissions including:

- Photo-acoustic sensor: Time-resolved PM emissions are determined by scaling the real-time measurement of soot in the exhaust to the gravimetric filter reference. The exhaust sample is exposed to modulated light which is absorbed by the soot particles causing periodic warming and cooling of the particles. The resulting expansion and contraction of the carrier gas generates a sound wave that is detected by microphones. Clean air produces no signal, but when the air is loaded with soot in exhaust gas, the signal rises proportionally to the concentration of soot in the measurement volume. The soot sensor does not respond to the volatile fractions of the PM. This is the more commonly used technique as it is relatively inexpensive but it is not approved for engine certification.

- Condensation particle counter (CPC): A particle counter that detects and counts aerosol particles by enlarging them using the particles as nucleation centres to create droplets in a supersaturated gas and then measuring the enlarged particles by laser scattering.

6 Preparing for testing – set-up

6.1 Investigation prior to emissions testing

Detailed research on the engine and its installation in the rolling stock should be conducted well in advance of testing to ascertain the range of parameters being measured for the engine and to allow the selection of appropriate equipment. Some of the information may be found in the available technical literature but for some items measurements may also need to be taken in advance to aid the equipment selection. Tables 3 and 4 contain the broad range of parameters to aid the start of the equipment selection process. Table 3 contains the minimum and maximum air, fuel and exhaust parameters for three different categories of rail engines and Table 4 contains the maximum level (for measurement purposes) of gaseous species and PM.

Table 3 Minimum and maximum air, fuel and exhaust parameters for three different categories of rail engine

	Units	**Small / medium engine DMU**	**Large engine DMU**	**Locomotive**
Fuel flow	kg/hr	40-180	50-150	30-1100
Fuel return	kg/hr	35-100	35-150	30-600
Air consumption	kg/hr	300-1850	350-4000	1000-20000
Exhaust gas flow	kg/hr	300-2000	400-4000	1000-20000
Exhaust gas back pressure	mbar	50	50	200
Exhaust gas temperature	°C	100-675	100-500	90-550

Table 4 Maximum level (for measurement purposes) of gaseous species and PM

Pollutant	**Units**	**Maximum measurement value**
CO_2	%	12
O_2	%	21
CO	ppm	1000
NO	ppm	1500
NO_2	ppm	100
NO_X	ppm	1750
HC	ppm	1000
PM	g/s	0.1

6.2 Engine preparation, mode test points and test sequences

This section covers the core aspects of which mode test points emissions should be measured at, for how long the engine should be run in those conditions, and in what sequence. Since the focus of this Testing Protocol is on evaluating real world conditions rather than those that form part of regulatory drive cycles, the mode test points recommended here relate to real world usage settings. In a few cases the mode test points recommended here will be the same as regulatory mode test points but in most cases they will be different. Testing is split into two aspects: testing the average emissions at mode test points assuming stable running conditions; and testing where emissions are not stable over time such as a cold start or SCR after transitioning to an extended period of idle. The need to test different idle settings corresponding to high, low and average (typical) loads is discussed in Section 3.5 of the Methodology Report.

The sampling time used for emissions analysis for each mode test point should be a minimum of 5 minutes but preferably longer. It should start once the engine has stabilised in a given mode. The US CFR (40 CFR 92 and 40 CFR 1033) methodology specifies a minimum of 10 minutes for full throttle running and a minimum of 15 minutes for the lowest idle power setting given the overall relative importance of those two modes to overall emissions both in real use and regulatory drive cycles. While these longer sampling times are practical for both diesel-electric locomotives and DMUs with electric transmission, it is less practical for DMUs with hydraulic or mechanical transmission where the number of individual test modes is far higher. Separate approaches are therefore taken for locomotive and diesel electric multiple unit (DEMU) engines with a small number of mode test points overall versus diesel hydraulic multiple unit (DHMU) or diesel mechanical multiple unit (DMMU) engines with a large number of individual mode test points, albeit with a number of common elements. The simpler locomotive/DEMU case is covered first below.

6.2.1 Locomotive and DEMU engine test modes and sequences for testing engines when installed on rolling stock

The US methodology for rail emissions testing recommends a "step pyramid"-type main testing sequence, starting at the lowest idle setting, then stepping up through each testing mode from lowest to highest power output (notch settings) and then back down again. The specified test points are the locomotive notch settings

One of the key learnings from the US methodology is to have a pre-testing phase where emissions, engine, fuel consumption and exhaust temperature data are recorded at idle and Notch 8 and are then analysed to assess whether the data aligns with expectations for engine performance and emissions before proceeding with the main testing sequence.

Confidence in emissions testing results for each mode test point comes partially from repeatability of testing at each mode test point. Three complete repeats of testing in each mode test point would normally be considered sufficient in this regard to achieve 95% confidence levels. However, two complete sets of testing for each mode test point and selected testing of some key mode test points for a third time would also achieve this. The US methodology is based on the latter with two sets of testing for all notches and a third set for a few notches, e.g. Idle and Notch 8, plus the use of pre-testing as well as Notch 8 and idle repeats after the main testing pyramid.

The US rail emission testing methodology has never directly taken into account the ISO 8178 mode test points or weightings, however the three test points for the ISO 8178 F cycle for locomotives are effectively included in the US approach with:

- Notch 8 being identical to the ISO 8178 F full power test mode
- Notch 3 or 4 (depending on the engine settings) closely but not exactly fulfilling the requirements for the ISO 8178 F intermediate power test mode
- Real idle running conditions for the engine as installed on the locomotive used as these can technically fulfil the criteria for regulatory idle.

Note that these settings have previously been used for ISO 8178 F drive cycle locomotive engine testing in Great Britain.

For most stationary type emissions testing of engines (either on or off-road engines) a sampling period is specified in the test requirements for each test point. Over each period the levels of individual emissions are averaged, the averaging only starting once the engine has achieved a stable running condition in that test mode. This means that the total time in each test mode is longer than the sampling period but in most cases is only slightly longer. Typical stabilising times can vary between 3 and 10 minutes depending on both the engine and the former and future mode test points (with larger differences in operating conditions between mode test points resulting in longer stabilising times). Stable running conditions in each mode test point are defined by:

- Charge air temperature (post turbocharger) - within +/-3 K from the average over the sampling period
- Exhaust gas temperature - within +/-3 K from the average value over the sampling period
- Engine speed (rpm) - within +/-5 rpm from the average value over the sampling period
- Engine power for non-Idle test mode points only - within +/-3% from the average value over the sampling period.

For locomotives used in passenger service and which provide electric train supply (ETS) to coaches, a second resistive loadbank will need to be used to create the representative ETS load.

As discussed in Section 5 of the Methodology Report, measuring average emissions under stable conditions at defined mode test points can lead to a very good understanding of overall emissions. However, there are several cases where the temporal evolution of emissions is of significant interest and averages over a typical measurement period will not provide useful insight. These include starting the engine (when the emissions vary over time and depend on the existing state of the engine e.g. hot, warm or cold) and the diminishing effectiveness of SCR at reducing NO and NO_2 emissions during the period of several minutes after there is a change from high to low power (e.g. Notch 8 to Idle). These two groups of situations can be addressed with dynamic scenarios where the emissions values on a second-by-second basis can be used to form a time series rather than averaged values.

Because of their specific significance to passenger and staff exposure in fixed locations, dynamic scenarios rather than fixed mode test points should be used for:

- Cold, warm and hot starts (when emissions will be higher than at 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 and brakes to a halt and the engine remains running at a fixed location e.g. replicating the approach to and calling at a station.

In rolling stock fitted with SCR abatement systems the NOx levels will initially be lower than at idle after a transition for high power running than when tested without SCR abatement systems. But after the engine starts to significantly cool, the SCR performance will drop and NOx 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 dynamic scenarios are easy to include in engine emissions testing if consideration is given during the planning of the sequencing of mode test points. Scenarios covering warm start, SCR operation from full power, SCR operation from half power, and hot start, are included at the end of main locomotive engine test sequence. The first mode test point in the sequence can be used to replicate a cold start.

Prior to testing, the engine, including auxiliary equipment and the exhaust system, should be conditioned according to the engine manufacturer's and/or user's recommendations in order to clean up the system and to achieve reliable test results. For example, any previous PM build up in the exhaust system should be removed by the preconditioning so that it is not counted if it were to be released during testing. This preconditioning is important for engines with long exhaust stacks and engines with silencers and/or exhaust aftertreatment systems in place.

The locomotive engine testing sequence is separated into two parts. Part 1 in Table 5 covers pre-testing and ends with a stop and review point where expectations for engine performance and emissions should be checked before then proceeding with the main testing sequence. Checks should include:

- Fuel consumption (is in line with expectation, see Spreadsheet 1 – Engine Settings, Drive Cycles and Test Results for values).
- Exhaust temperatures (are in line with expectation, see Spreadsheet 1 – Engine Settings, Drive Cycles and Test Results for values).
- For Methods 1, 2 and 4 (see Section 4), that the carbon and oxygen balances are within required tolerances.
- Measured gases and PM levels in the exhaust stream are in line with general expectations.

The pre-testing sequence should take less than 35 minutes in total.

Table 5 Locomotive testing sequence Part 1 (pre-testing)

Sequence number	Test mode	Notch setting	Expected total time in mode (minutes)	Sample averaging period for emissions	Include average in final emissions data?	Dynamic emissions recording?	Specific purpose?
1	Pre-test Idle	Lowest idle setting	5 to 10	300 ±5 seconds	No	n/a	Pre-test check
2	Pre-test full power	Notch 8	10 to 15	300 ±5 seconds	No	n/a	Pre-test check
3	Pre-test Idle	Lowest idle setting	5 to 10	300 ±5 seconds	No	n/a	Pre-test check
4	**Stop and review point**						

Part 2 of the locomotive engine testing sequence which includes the core mode test points is shown in Table 6. The main testing sequence should take a maximum of 5 hours in total (assuming the engine requires longer to settle with stable conditions at each change) but with a realistic minimum time of 3.5 hours.

Table 6 Locomotive testing sequence Part 2 (main testing)

Sequence number	**Test mode**	**Notch setting**	**Expected total time in mode (minutes)**	**Sample averaging period for emissions**	**Include average in final emissions data?**	**Dynamic emissions recording?**	**Specific purpose?**
5	A	Lowest idle setting[1]	15	*Not applicable*	No	**Yes**	**Cold Start**
6	A	Low idle[2]	5 to 10	300 ±5 seconds	Yes	No	Core testing
7	B	Normal idle	5 to 10	300 ±5 seconds	Yes	No	Core testing
8	1	Notch 1	5 to 10	300 ±5 seconds	Yes	No	Core testing
9	2	Notch 2	5 to 10	300 ±5 seconds	Yes	No	Core testing
10	3	Notch 3	5 to 10	300 ±5 seconds	Yes	No	Core testing
11	4	Notch 4	5 to 10	300 ±5 seconds	Yes	No	Core testing
12	5	Notch 5	5 to 10	300 ±5 seconds	Yes	No	Core testing
13	6	Notch 6	5 to 10	300 ±5 seconds	Yes	No	Core testing
14	7	Notch 7	5 to 10	300 ±5 seconds	Yes	No	Core testing
15	8	Notch 8	10 to 15	600 ±5 seconds	Yes	No	Core testing
16	7	Notch 7	5 to 10	300 ±5 seconds	Yes	No	Core testing
17	6	Notch 6	5 to 10	300 ±5 seconds	Yes	No	Core testing
18	5	Notch 5	5 to 10	300 ±5 seconds	Yes	No	Core testing
19	4	Notch 4	5 to 10	300 ±5 seconds	Yes	No	Core testing
20	3	Notch 3	5 to 10	300 ±5 seconds	Yes	No	Core testing

Sequence number	**Test mode**	**Notch setting**	**Expected total time in mode (minutes)**	**Sample averaging period for emissions**	**Include average in final emissions data?**	**Dynamic emissions recording?**	**Specific purpose?**
21	2	Notch 2	5 to 10	300 ±5 seconds	Yes	No	Core testing
22	1	Notch 1	5 to 10	300 ±5 seconds	Yes	No	Core testing
23	B	Normal idle	5 to 10	300 ±5 seconds	Yes	No	Core testing
24	Off	Engine Off	15	*Not applicable*	No	No	**Warm Start**
25	B	Normal idle	5 to 10	300 ±5 seconds	No	**Yes**	
26	8	Notch 8	5 to 10	300 ±5 seconds	No	**Yes**	**SCR from full power**
27	B	Normal idle	15	750 ±5 seconds	No	**Yes**	
28	8	Notch 4	5 to 10	300 ±5 seconds	No	**Yes**	**SCR from half power**
29	B	Normal idle	15	750 ±5 seconds	No	**Yes**	
30	Off	Engine Off	3	*Not applicable*	No	No	**Hot Start**
31	B	Normal idle	5 to 10	300 ±5 seconds	No	**Yes**	

[1] On many locomotives designs the idle RPM depends on auxiliary loads and engine cooling requirements so the aim is to minimise both, however for cold engines the ECU will often use the higher rpm and fuel use of Normal Idle to warm the engine faster. Hence the engine may only run in Normal Idle rather than Low Idle and using real world conditions. The aim of this part of the testing sequence is to help understand the emissions impact of engine starts and warm the engine up for the main step pyramid of testing.

[2] After the previous Step 5 ("cold start") the engine should be able to run in Low Idle with reduced rpm and fuel consumption.

6.2.2 DHMU/DMMU engine test modes and sequences for testing engines on dynamometers

The DHMU and DMMU engine test modes and sequences for testing engines on dynamometers have both similarities and differences to the locomotive and DEMU (on-board) modes and sequences.

Similarities are:

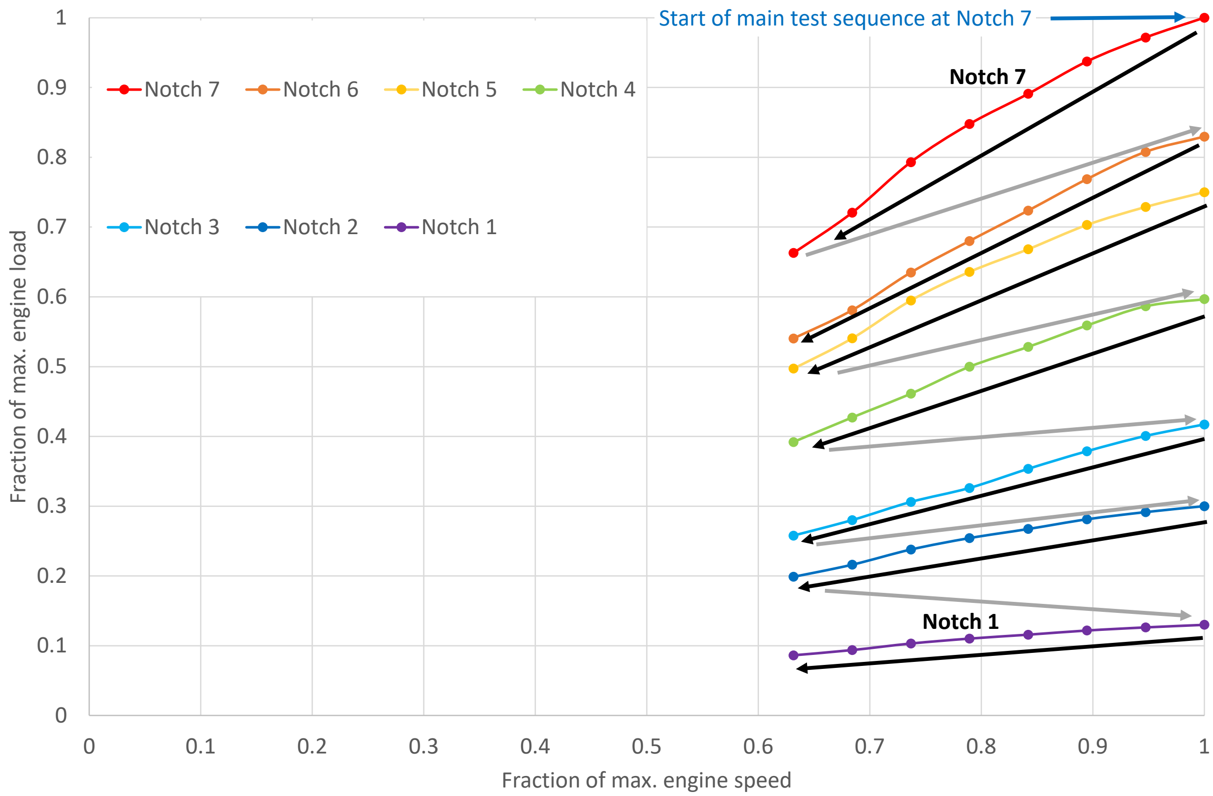
- Pre-testing
- Dynamic scenarios (to evaluate engine start-up emissions and potential SCR effectiveness)
- Engine stabilisation requirements after changing mode.

Differences are:

- The requirement to specify notch, engine rpm and engine load (kW) rather than just notch for each mode test point
- Pre-testing includes an extra mode test point so both the highest and lowest specified rpm in the highest notch are included. (A substantial difference in exhaust temperature and some gaseous emissions (e.g. NOx) is expected between the highest and lowest specified rpm in the highest notch.)
- Shorter average sampling time, 3 minutes instead of 5 minutes at each mode test point
- The main testing sequence starts at maximum power and rpm, e.g. Notch 7 at maximum rpm, then for the next step in the testing sequence the engine rpm decreases. Reducing (rather than increasing) the engine rpm and applied dynamometer load for the majority of changes minimises the time taken for the engine to stabilise, thus helping to minimise overall testing time. After testing at the lowest engine rpm in each notch, the next step in the sequence is to change to the maximum rpm in the next lowest notch. This transition sequence is illustrated in Figure 4.
- The repeat of the mode test points is achieved by repeating the whole main test sequence rather than stepping down the pyramid for the locomotive testing.

Confidence in the testing results is achieved despite shorter average sampling times (than for locomotive testing) with the combination of two repeats of the main testing sequence (Steps 6 to 103 in the example below) and significantly larger number of mode test points which give more confidence in the robustness of the data through comparison with the adjacent points.

Figure 4 Diagram illustrating the test sequence for Notch 1-7 mode test points



Dynamometer load settings for each mode test point are included in the "Engine settings, Drive cycle and Test Results" spreadsheet. Many DHMU engines (effectively all on the more modern DHMU designs) and all DMMU engines are controlled indirectly via the transmission and these engines are tested post overhaul with a dynamometer attached to the transmission rather than the engine. This potentially makes controlling the engine during emission testing relatively easy if there are no changes to existing engine settings. However, it would be impossible or very difficult to recreate certain mode test points with the existing transmission attached. This is only a potential issue if the aim of the testing includes gathering emissions data for mode test points under which the engine does not currently operate. For example, to be able to model the emission impact of a potential change in transmission (e.g. replacing the existing hydraulic transmission with a new mechanical one). In such cases there will have to be some development and design work needed, firstly to understand the control signals that the ECU would normally receive from the transmission, and secondly be able to produce such control signals as required to control the engine during testing.

In older DHMU designs (e.g. BR era designs) the engine is directly controlled via the electronic throttle signals. For these engines this set-up provides significant flexibility to gather the data in all mode test points by controlling just the four binary control signals to the four fuel solenoids.

The pre-testing sequence is similar to the locomotive sequence in Table 5 and is outlined in Table 7 below. It should take less than 45 minutes in total.

Table 7 Illustrative DHMU/DMMU testing sequence Part 1 (pre-testing)

Sequence number	**Notch setting**	**Engine RPM**	**Expected total time in mode (minutes)**	**Sample averaging period for emissions**	**Include average in final emissions data?**	**Dynamic emissions recording?**	**Specific purpose?**
1	Idle (Low)	800	5 to 10	300 ±5 seconds	No	n/a	Pre-test check
2	Pre-test Full, max RPM	1900	10 to 15	300 ±5 seconds	No	n/a	Pre-test check
3	Pre-test Full, maximum torque RPM	1350	5 to 10	300 ±5 seconds	No	n/a	Pre-test check
4	Idle (Low)	800	5 to 10	300 ±5 seconds	No	n/a	Pre-test check
5	**Stop and review point**						

Part 2 of the DHMU/DMMU engine testing sequence which includes the core mode test points is shown in Table 8. The main testing sequence should take between 6.5 and 9 hours in total (depending on how long the engine takes to settle with stable conditions at each change). Hence this makes it ideal to run one repeat main test cycle during the working day or on more automated test cells run both the main sequences overnight (only applicable to the larger test facilities). If the main testing sequence needs to be stopped and then restarted later on, Steps 1-4 of the pre-testing sequence in Table 7 should be repeated, then restart the main test sequence following on immediately (without a pause) at the maximum rpm in the notch being tested. The sequence of mode test point in Notches 1-7, with the black arrows showing the sequence within each notch and the grey arrows the transition between notches, is shown in Figure 4. .

Table 8 Illustrative DHMU/DMMU testing sequence Part 1 (main testing)

Sequence number	**Notch setting**	**Engine RPM**	**Expected total time in mode (minutes)**	**Sample averaging period for emissions**	**Include average in final emissions data?**	**Dynamic emissions recording?**	**Specific purpose?**
6	Idle (Low)	800	15	Not applicable	No	Yes	Cold Start

Sequence number	Notch setting	Engine RPM	Expected total time in mode (minutes)	Sample averaging period for emissions	Include average in final emissions data?	Dynamic emissions recording?	Specific purpose?
7	Idle (typical average)	800	3 to 5	180 ±5 seconds	Yes	No	Core testing
8	Idle (High)	800	3 to 5	180 ±5 seconds	Yes	No	Core testing
9	Notch 7	1900	3 to 5	180 ±5 seconds	Yes	No	Core testing
10	Notch 7	1850	3 to 5	180 ±5 seconds	Yes	No	Core testing
11	Notch 7	1800	3 to 5	180 ±5 seconds	Yes	No	Core testing
12	Notch 7	1750	3 to 5	180 ±5 seconds	Yes	No	Core testing
13	Notch 7	1700	3 to 5	180 ±5 seconds	Yes	No	Core testing
14	Notch 7	1650	3 to 5	180 ±5 seconds	Yes	No	Core testing
15	Notch 7	1600	3 to 5	180 ±5 seconds	Yes	No	Core testing
16	Notch 7	1550	3 to 5	180 ±5 seconds	Yes	No	Core testing
17	Notch 7	1500	3 to 5	180 ±5 seconds	Yes	No	Core testing
18	Notch 7	1450	3 to 5	180 ±5 seconds	Yes	No	Core testing
19	Notch 7	1400	3 to 5	180 ±5 seconds	Yes	No	Core testing
20	Notch 7	1350	3 to 5	180 ±5 seconds	Yes	No	Core testing
21	Notch 6	1900	3 to 5	180 ±5 seconds	Yes	No	Core testing
22	Notch 6	1850	3 to 5	180 ±5 seconds	Yes	No	Core testing
23	Notch 6	1800	3 to 5	180 ±5 seconds	Yes	No	Core testing

Sequence number	Notch setting	Engine RPM	Expected total time in mode (minutes)	Sample averaging period for emissions	Include average in final emissions data?	Dynamic emissions recording?	Specific purpose?
24	Notch 6	1750	3 to 5	180 ±5 seconds	Yes	No	Core testing
25	Notch 6	1700	3 to 5	180 ±5 seconds	Yes	No	Core testing
26	Notch 6	1650	3 to 5	180 ±5 seconds	Yes	No	Core testing
27	Notch 6	1600	3 to 5	180 ±5 seconds	Yes	No	Core testing
28	Notch 6	1550	3 to 5	180 ±5 seconds	Yes	No	Core testing
29	Notch 6	1500	3 to 5	180 ±5 seconds	Yes	No	Core testing
30	Notch 6	1450	3 to 5	180 ±5 seconds	Yes	No	Core testing
31	Notch 6	1400	3 to 5	180 ±5 seconds	Yes	No	Core testing
32	Notch 6	1350	3 to 5	180 ±5 seconds	Yes	No	Core testing
33	Notch 5	1900	3 to 5	180 ±5 seconds	Yes	No	Core testing
34	Notch 5	1850	3 to 5	180 ±5 seconds	Yes	No	Core testing
35	Notch 5	1800	3 to 5	180 ±5 seconds	Yes	No	Core testing
36	Notch 5	1750	3 to 5	180 ±5 seconds	Yes	No	Core testing
37	Notch 5	1700	3 to 5	180 ±5 seconds	Yes	No	Core testing
38	Notch 5	1650	3 to 5	180 ±5 seconds	Yes	No	Core testing
39	Notch 5	1600	3 to 5	180 ±5 seconds	Yes	No	Core testing
40	Notch 5	1550	3 to 5	180 ±5 seconds	Yes	No	Core testing

Sequence number	Notch setting	Engine RPM	Expected total time in mode (minutes)	Sample averaging period for emissions	Include average in final emissions data?	Dynamic emissions recording?	Specific purpose?
41	Notch 5	1500	3 to 5	180 ±5 seconds	Yes	No	Core testing
42	Notch 5	1450	3 to 5	180 ±5 seconds	Yes	No	Core testing
43	Notch 5	1400	3 to 5	180 ±5 seconds	Yes	No	Core testing
44	Notch 5	1350	3 to 5	180 ±5 seconds	Yes	No	Core testing
45	Notch 4	1900	3 to 5	180 ±5 seconds	Yes	No	Core testing
46	Notch 4	1850	3 to 5	180 ±5 seconds	Yes	No	Core testing
47	Notch 4	1800	3 to 5	180 ±5 seconds	Yes	No	Core testing
48	Notch 4	1750	3 to 5	180 ±5 seconds	Yes	No	Core testing
49	Notch 4	1700	3 to 5	180 ±5 seconds	Yes	No	Core testing
50	Notch 4	1650	3 to 5	180 ±5 seconds	Yes	No	Core testing
51	Notch 4	1600	3 to 5	180 ±5 seconds	Yes	No	Core testing
52	Notch 4	1550	3 to 5	180 ±5 seconds	Yes	No	Core testing
53	Notch 4	1500	3 to 5	180 ±5 seconds	Yes	No	Core testing
54	Notch 4	1450	3 to 5	180 ±5 seconds	Yes	No	Core testing
55	Notch 4	1400	3 to 5	180 ±5 seconds	Yes	No	Core testing
56	Notch 4	1350	3 to 5	180 ±5 seconds	Yes	No	Core testing
57	Notch 3	1900	3 to 5	180 ±5 seconds	Yes	No	Core testing

Sequence number	Notch setting	Engine RPM	Expected total time in mode (minutes)	Sample averaging period for emissions	Include average in final emissions data?	Dynamic emissions recording?	Specific purpose?
58	Notch 3	1850	3 to 5	180 ±5 seconds	Yes	No	Core testing
59	Notch 3	1800	3 to 5	180 ±5 seconds	Yes	No	Core testing
60	Notch 3	1750	3 to 5	180 ±5 seconds	Yes	No	Core testing
61	Notch 3	1700	3 to 5	180 ±5 seconds	Yes	No	Core testing
62	Notch 3	1650	3 to 5	180 ±5 seconds	Yes	No	Core testing
63	Notch 3	1600	3 to 5	180 ±5 seconds	Yes	No	Core testing
64	Notch 3	1550	3 to 5	180 ±5 seconds	Yes	No	Core testing
65	Notch 3	1500	3 to 5	180 ±5 seconds	Yes	No	Core testing
66	Notch 3	1450	3 to 5	180 ±5 seconds	Yes	No	Core testing
67	Notch 3	1400	3 to 5	180 ±5 seconds	Yes	No	Core testing
68	Notch 3	1350	3 to 5	180 ±5 seconds	Yes	No	Core testing
69	Notch 2	1900	3 to 5	180 ±5 seconds	Yes	No	Core testing
70	Notch 2	1850	3 to 5	180 ±5 seconds	Yes	No	Core testing
71	Notch 2	1800	3 to 5	180 ±5 seconds	Yes	No	Core testing
72	Notch 2	1750	3 to 5	180 ±5 seconds	Yes	No	Core testing
73	Notch 2	1700	3 to 5	180 ±5 seconds	Yes	No	Core testing
74	Notch 2	1650	3 to 5	180 ±5 seconds	Yes	No	Core testing

Sequence number	Notch setting	Engine RPM	Expected total time in mode (minutes)	Sample averaging period for emissions	Include average in final emissions data?	Dynamic emissions recording?	Specific purpose?
75	Notch 2	1600	3 to 5	180 ±5 seconds	Yes	No	Core testing
76	Notch 2	1550	3 to 5	180 ±5 seconds	Yes	No	Core testing
77	Notch 2	1500	3 to 5	180 ±5 seconds	Yes	No	Core testing
78	Notch 2	1450	3 to 5	180 ±5 seconds	Yes	No	Core testing
79	Notch 2	1400	3 to 5	180 ±5 seconds	Yes	No	Core testing
80	Notch 2	1350	3 to 5	180 ±5 seconds	Yes	No	Core testing
81	Notch 1	1900	3 to 5	180 ±5 seconds	Yes	No	Core testing
82	Notch 1	1850	3 to 5	180 ±5 seconds	Yes	No	Core testing
83	Notch 1	1800	3 to 5	180 ±5 seconds	Yes	No	Core testing
84	Notch 1	1750	3 to 5	180 ±5 seconds	Yes	No	Core testing
85	Notch 1	1700	3 to 5	180 ±5 seconds	Yes	No	Core testing
86	Notch 1	1650	3 to 5	180 ±5 seconds	Yes	No	Core testing
87	Notch 1	1600	3 to 5	180 ±5 seconds	Yes	No	Core testing
88	Notch 1	1550	3 to 5	180 ±5 seconds	Yes	No	Core testing
89	Notch 1	1500	3 to 5	180 ±5 seconds	Yes	No	Core testing
92	Notch 1	1350	3 to 5	180 ±5 seconds	Yes	No	Core testing
93	Idle (High)	800	3 to 5	180 ±5 seconds	Yes	No	Core testing

Sequence number	Notch setting	Engine RPM	Expected total time in mode (minutes)	Sample averaging period for emissions	Include average in final emissions data?	Dynamic emissions recording?	Specific purpose?
94	Idle (typical average)	800	3 to 5	180 ±5 seconds	Yes	No	Core testing
95	Idle (Low)	800	3 to 5	180 ±5 seconds	Yes	No	Core testing
96	Engine Off	-	15	*Not applicable*	No	No	Warm Start
97	Idle (typical average)	800	5 to 10	300 ±5 seconds	No	**Yes**	
98	Notch 7	1350	5 to 10	300 ±5 seconds	No	**Yes**	SCR from Full
99	Idle (typical average)	800	15	750 ±5 seconds	No	**Yes**	
100	Notch 4	1900	5 to 10	300 ±5 seconds	No	**Yes**	SCR from Half
101	Idle (typical average)	800	15	750 ±5 seconds	No	**Yes**	
102	Engine Off	-	3	*Not applicable*	No	No	Hot Start
103	Idle (typical average)	800	5 to 10	300 ±5 seconds	No	**Yes**	

To derive emissions across the relevant drive cycle, emissions for each mode test point will need to be weighted appropriately for each specific rolling stock class and this is discussed in Section 11.

6.3 Fuel testing

For engine development and emissions R&D programmes the use of reference fuels with tightly controlled specifications is usually required. This reduces an opportunity for a variation in the test and potentially allows for better comparability across different sets of tests. However, reference fuels can be very different to current fuels used in GB rail operations and as the focus is on real world emissions and in some cases changes in fuels it is therefore more sensible to use fuel from the operator's usual supply chain as the default fuel. It is important that the exact fuel specification is known so that the effects of small differences in fuel that may result in differences in measured emissions are known and the effect on emissions can be fully understood. For example, the trace mineral content in fuel usually ends up in particulate matter emissions hence potential variations in mineral content need to be understood (mineral origin particulate matter is not removed by Diesel Oxidation Catalyst (DOC) but is by diesel particulate filter (DPF) so this can have a noticeable effect on potential residual emissions after the installation of exhaust abatement measures) where only a DOC is fitted as is the case with some Stage IIIB complaint engines.

Hence laboratory testing of the fuel for the items set out in first sub-section of 7 needs to be planned and arranged in advance of emission testing.

The current diesel fuel specified in the UK for rail use is Gas Oil compliant to BS2869:2017 A2 with 7% FAME inclusion. To simplify fuel distribution in many areas of the country through reducing the number of fuel grades distributed, road diesel, complying to the identical or slightly stricter requirements of EN590 with the required red dye additive, is often supplied instead of Gas Oil. Hence fuel testing is important to characterise the fuel that is actually used by the operator and the test facility and if there are potential differences between them.

6.4 Ambient conditions

Ambient conditions have significant impact on the accuracy of emissions testing measurements and calculation of emission factors (which involves some standardisation of test conditions) hence the importance of recording the ambient conditions required for the calculations during testing and aligned to each test mode where needed.

The f_a value, a measure of how far overall ambient conditions during testing differ from the default standard values, should be stated with the results of the tests so it can readily be understood how far away the test conditions were from the standard conditions.

6.5 Power

Engine power and its measurement for all relevant ISO standards are defined in ISO 14396. For regulatory purposes the basis of specific emissions measurement is uncorrected brake power when g/kWh is used. Power, engine speed and torque values may differ and be less accurate in the field compared to the testbed conditions. Therefore, the emission values expressed in g/kWh may differ in the field compared to those under test-bed conditions.

The appropriate engine power output should be recorded for each operating condition or mode.

For laboratory-based testing, the instrumentation for torque and speed measurement should enable the measurement of the shaft power to be within the given limits. For field-based testing of diesel-electric transmission rolling stock power is measured directly rather than being calculated from torque and engine speed.

In some cases, signals from the ECU may be used in place of values measured by individual instruments, provided the signals are correctly filtered and time-aligned with the emissions signals from the test instruments.

A combination of ECU signals, with or without other measurements, may be used to estimate engine speed and torque for use in brake-specific emission calculations, provided the overall accuracy and repeatability is sufficient.

6.6 Preference for ideally raw gaseous emissions testing

The total mass of the pollutants generated during each test mode is ideally determined by calculating the instantaneous mass emissions from the raw concentrations of the pollutants and the exhaust mass flow and integrating the instantaneous values over the test mode for the highest overall accuracy. Preferably, the concentrations should be measured on a wet basis. If measured on a dry basis, the dry/wet correction (see Step 10 in Section 8.10) should be applied to the instantaneous concentration values before any further calculation is done.

6.7 Positioning emission sampling equipment

Installation of the sampling probes and measuring equipment are described in ISO 8178-1:2020 Parts 7 and 8. Particular care should be taken especially for smaller engines and those with abatement systems that the connectors and tubing associated with exhaust sampling should not increase back pressure so much that it exceeds the manufacturer's maximum specified exhaust restriction. Also, similarly for field-based testing at lower engine powers /exhaust mass flow, care should be taken, if possible, to avoid testing during high wind speeds in the open where the wind can substantially alter the exhaust plume and potentially affect testing.

The gaseous emissions sampling probes need to be fitted at least 0.5 m or three times the diameter of the exhaust pipe, whichever is larger, upstream of the exit of the exhaust gas system but sufficiently close to the engine as to ensure an exhaust gas temperature of at least 70°C at the probe. Conversely, the US approach is focused on larger locomotive engines (it was developed for measuring emissions from large static exhaust stacks) and specifies a minimum of 8 times the diameter of sufficiently smooth flow of the exhaust gas stream before the sampling probes to enable the exhaust gas velocity (if required) to be accurately measured at the same point as the gas analysis, PM and exhaust temperature probes. In practice this requires a duct slightly larger than the exhaust diameter (with all the probes mounted on it) being used to extend the exhaust system. If high accuracy of fuel and air flow measurements can be guaranteed (typically with the use of temperature corrected fuel flow gauges) there is no need to measure exhaust gas velocity to be able to accurately calculate exhaust mass flow.

If the engine is equipped with an exhaust aftertreatment system (e.g. DOC, SCR or DPF), the exhaust samples are taken downstream of the exhaust aftertreatment system.

6.8 Exhaust gas flow

The principal methods applicable for determining the exhaust gas flow are described in ISO 8178-1:2006 Section 7.3. For the accuracy required, see Section 7.4 of this part of ISO 8178.

6.9 Calibration of the analytical instruments

The definitions and requirements given in ISO 8178-1:2020 Clause 8, and ISO 8178-11:2005 Section 11.3, apply with the exception of the calibration points.

6.10 Engine control during testing

Locomotives (and some DEMUs) are designed to be able to conduct testing (e.g. post engine overhaul) on resistive load banks and controlled with the existing cab controls. This is not the case for a DMU engine removed from the rolling stock for dynamometer testing. To accurately control DMU engines during dynamometer testing custom control electronics will need to be developed prior to testing (unless the test facility has previously been used to conduct rail engine testing on those engines). On older British Rail-era DMU classes this is relatively simple, just requiring replication of the signals from the throttle lever to the solenoids that control the fuel flow to the injectors. However, the situation is more complex on more recent post privatisation designs where there is computerised control of the transmission and the throttle signals are sent to the transmission controller which then controls the engine. This leads to two different scenarios, if the engine is being tested complete with the transmission (often the case with post overhaul testing) then suitable control electronics need to be developed to correctly interact with the transmission which will then control the engine or if the engine is being tested without the transmission then the wider and more complex range of control signals that the transmission sends to the engine will need to be replicated. Dual fuel mitigation options using liquified natural gas (LNG), compressed natural gas (CNG), or Hydrogen which involve partial substitution of diesel or modern fuel injection system replacement solutions will involve the development of new ECU solutions which will have to be capable of dynamometer testing for development work effectively resolving the challenge in those cases.

7 Conducting testing – required data, accuracy and precision

7.1 Non-emissions data items

Emissions testing involves far more than just the measuring of pollutant concentrations. A listing of the other parameters that need to be measured before and during the test is given here.

- **Fuel chemistry and physical properties** –all calculation methods
  - Lower and higher heating values per unit mass of fuel (MJ/kg)
  - % mass of carbon per unit mass of fuel
  - % mass of hydrogen per unit mass of fuel
  - % mass of oxygen per unit mass of fuel
  - % mass of nitrogen per unit mass of fuel
  - % mass of sulphur per unit mass of fuel
  - % mass of Polycyclic aromatic hydrocarbons (PAH) per unit mass of fuel
  - % mass of ash (mineral content) per unit mass of fuel
  - % mass of particulates per unit mass of fuel
  - % mass of water per unit mass of fuel
  - % volume of fatty acid methyl ester (FAME) per unit volume of fuel [EN590 Diesels]
  - Fuel density at 15°C (kg/m^3)
  - Kinematic viscosity at 40°C (mm^2/s) [Liquid fuels]
  - Cetane number [EN590 Diesels]
  - Mean specific heat capacity over 0 – 100°C (KJ/kg °C)
  - Volumetric correction factor (per °C)
- **Ambient conditions (throughout testing)** – data needed varies by calculation method
  - Ambient temperature
  - Windspeed
  - Total atmospheric pressure
  - Dry atmospheric pressure
- **Intake air conditions (throughout testing)** – data needed varies by calculation method
  - Temperature of intake air

    - Saturation vapour pressure intake air
    - Relative Humidity of intake air
    - Absolute humidity of intake air
    - Oxygen content of dry intake air
- **Intake air mass flow (throughout testing)** – some calculation methods only
- **Additional engine data** (in each engine running condition through testing)
    - Charge air temperature (post turbocharger)
    - Engine speed (rpm)
    - Air manifold pressure
    - Exhaust gas temperature
- **Fuel consumption (throughout testing)** – some calculation methods only
    - Temperature corrected fuel and return flow rates measured using high accuracy flow gauges and data logger to calculate net fuel use
- **Engine power data (electrical transmission)**
    - Main alternator voltage
    - Main alternator current
    - Auxiliary alternator voltage
    - Auxiliary alternator current
    - Approximate power consumption of mechanical auxiliary loads
- **Engine power data - hydraulic or mechanical transmission** (throughout testing)
    - Dynamometer power
    - Dynamometer torque
- **Exhaust mass flow (throughout testing)** – some calculation methods only
    - Exhaust gas temperature
    - Exhaust gas pressure differential (with stainless S-type pitot tube) in a suitable duct - if there are accuracy issues with fuel mass flow accuracy and exhaust mass flow is being directly measured
- **Additional emissions measuring equipment data (throughout testing)** – should not change
    - Temperature of the cooling bath (part of the analysis equipment)
    - Water pressure after the cooling bath (part of the analysis equipment)
- **Bosch Smoke Number (throughout testing)**
    - Acts as a good general measure of engine health and combustion quality rather than as substitute for Particulate Mass (PM) or Particulate Number (PN) particulate measurement.

7.2 Measuring equipment accuracy

The exhaust gas analyser should not deviate from the nominal calibration point by more than ±4% of the reading or ±0.5% of full scale, whichever is larger, and the accuracy should be determined according to the calibration requirements laid down in ISO 8178-1:2020 8.5.

The accuracy of the measuring equipment should be such that the permissible deviations given in Tables 9 and 10 are not exceeded. These deviations refer to the final recorded value, which is inclusive of the data acquisition system. The calibration of all measuring instruments should be traceable to national or international standards. The instruments should be calibrated as required by internal audit procedures, ideally by the instrument manufacturer or in accordance with ISO 9000 requirements.

Table 9 Permissible deviations of instruments for engine-related parameters (if measured)

Item	Permissible deviation based on maximum engine values
Engine speed	±0.5%
Torque	±5%
Power	±5%
Fuel consumption	±0.5%* (Method 3, preferably lower) ±4% (Methods 1 and 2)
Air consumption (if measured)	±5%
Exhaust gas flow (if measured)	±5% calculated

* ±2.5% for Method 3 fuel consumption at idle

While fundamental parameters are listed in Table 9 it is also important to ensure other parameters listed in Table 10 are also measured with sufficient accuracy so that the overall calculation accuracy is not degraded. In many cases the tolerances listed here are smaller than the permissible deviations given in Table 4 of ISO 15550:2002, which is mainly focused on (smaller) road engines where the deviation has a smaller overall impact on emission testing results compared to larger rail engines and modern digital instruments can easily achieve these accuracies if correctly installed which because of what the need to ensure is achievable.

Table 10 Permissible values for key data items

Item	Permissible deviation from absolute values "of reading"
Exhaust gas pressure	±5% of reading
Exhaust gas temperature	±15 K
Air intake temperature (combustion air)	±2 K
Atmospheric pressure	±0.5% of reading
Intake air humidity (relative)	±3%
Fuel temperature	±2 K
Dilution tunnel temperatures	±1.5 K
Dilution air humidity (relative)	±3%
Diluted exhaust gas flow	±2% of reading

7.3 Accuracy and precision of test results

Field measurements are typically less precise and less accurate than measurements on a test bed due to environmental and operational impacts. Overall precision and accuracy also depend on the measuring units, e.g. volume concentration (ppm), mass concentration (μg/m^3) or brake-specific emission (g/kWh). From the accuracies as specified in ISO 8178-1, 7.5.1.2 and 9.2, and in Table 5, the expected accuracy and precision of the measurement results are calculated and are given in Table 11.

Table 11 Necessary accuracy and precision of test results

Component	Unit	Accuracy	Precision
Gaseous Emissions	ppm	±5% of reading	±1% of reading
	μg/m^3	±7%	±5.1%
	g/kWh	±9%	±7.4%
Particulate Emissions	μg/m^3	±6.5%	±6.5%
	g/kWh	±8.5%	±8.5%
Note: The given values are only valid under ideal testing conditions. In practice these conditions do not always exist, especially for field-based testing where the accuracy and precision will be lower unless necessary adjustments are made.			

8 Post testing – performing calculations

The calculation steps in this section have been synthesized primarily from relevant material in ISO Standard 8178, the US CFR and UNECE R49, and then adapted to suit the needs of the GB rail industry. See the bibliography in Section 13 for a full set of references.

The structure of this section follows that of the associated Spreadsheet 2 (Emissions Calculations Template). Calculations are grouped together; for example, Step 1 contains all the initial calculations based on fuel chemistry data, Step 2 contains all the initial calculations based on atmospheric parameters. A calculation is usually done at the earliest logical step where all the data items are available even if the value from the calculation is not used till several steps later, since this helps simplify some of the very complex calculation steps in the middle of the process.

The accompanying spreadsheet contains four columns (on the far left) where the applicability of each calculation step to each calculation method is shown. This is also summarised in the Table 12.

Table 12 Summary of applicability of calculation steps for each calculation method

	Method 1: Air and fuel measurement	**Method 2: Tracer gas**	**Method 3: Fuel flow measurement and chemical balance**	**Method 4: air and air-to-fuel ratio measurement**
Step 1	Yes	Some	Yes	Yes
Step 2	Yes	Yes	Yes	Yes
Step 3	Yes		Yes	Yes
Step 4	Yes		Yes	Yes
Step 5	Yes	Yes	Yes	Yes
Step 6	Useful check		Useful check	Yes
Step 7	Useful check		Useful check	Yes
Step 8	Useful check		Yes	Useful check
Step 9	Yes - parts relevant to method	Yes - parts relevant to method	Yes - parts relevant to method	Yes - parts relevant to method
Step 10	Yes	Yes	Yes	Yes
Step 11	Yes	Yes	Yes	Yes
Step 12	Yes	Yes	Yes	Yes
Step 13	Yes	Yes	Yes	Yes
Step 14	Yes	Yes	Yes	Yes
Step 15	Yes	Yes	Yes	Yes
Step 16	Yes	Yes	Yes	Yes
Step 17	Yes	Yes	Yes	Yes
Step 18	Yes	Yes	Yes	Yes

8.1 Step 1 – Fuel parameters

Accurately understanding the fuel chemistry is key to being able to calculate accurate emissions (unless using Method 2 Tracer Gas). Hence a sample of fuel used in the testing needs to be sent to a laboratory for analysis and the results returned before the emission calculations can be completed, although some calculations can be done while this takes place.

The chemical formula of the fuel can be written as $C_{\beta}H_{\alpha}O_{\varepsilon}S_{\gamma}N_{\delta}$. The fuel composition data α, β, γ, δ, ε are defined as the molar ratios of H, C, S, N and O related to C (chemical formula of the fuel $CH_{\alpha}O_{\varepsilon}S_{\gamma}N_{\delta}$, related to one carbon atom per molecule). The relation to one carbon atom per theoretical molecule is used because the real number of carbon atoms per an average fuel molecule is not known with real fuels. This relationship does not work with non-carbon fuels. The fuel composition data w_H, w_C, w_S, w_N and w_O are defined as the % mass of H, C, S, N and O. The following formulae give the conversion between the two sets of data (when β = 1) and A_r is the relative atomic mass of the species:

$$\alpha = \frac{\frac{w_{\mathrm{H}}}{A_{\mathrm{rH}}}}{\frac{w_{\mathrm{C}}}{A_{\mathrm{rC}}}} = 11.9164 \times \frac{w_{\mathrm{H}}}{w_{\mathrm{C}}} \tag{4}$$

$$\beta = \frac{\frac{w_{\mathrm{C}}}{A_{\mathrm{rC}}}}{\frac{w_{\mathrm{C}}}{A_{\mathrm{rC}}}} = 1 \tag{5}$$

$$\gamma = \frac{\frac{w_{\mathrm{S}}}{A_{\mathrm{rS}}}}{\frac{w_{\mathrm{C}}}{A_{\mathrm{rC}}}} = 0.37464 \times \frac{w_{\mathrm{S}}}{w_{\mathrm{C}}} \tag{6}$$

$$\delta = \frac{\frac{w_{\mathrm{N}}}{A_{\mathrm{rN}}}}{\frac{w_{\mathrm{C}}}{A_{\mathrm{rC}}}} = 0.85752 \times \frac{w_{\mathrm{N}}}{w_{\mathrm{C}}} \tag{7}$$

$$\varepsilon = \frac{\frac{w_{\mathrm{O}}}{A_{\mathrm{rO}}}}{\frac{w_{\mathrm{C}}}{A_{\mathrm{rC}}}} = 0.75072 \times \frac{w_{\mathrm{O}}}{w_{\mathrm{C}}} \tag{8}$$

$$w_{\mathrm{H}} = \frac{\alpha \times A_{\mathrm{rH}} \times 100}{M_{\mathrm{rf}}} \tag{9}$$

$$w_{\mathrm{C}} = \frac{\beta \times A_{\mathrm{rC}} \times 100}{M_{\mathrm{rf}}} \tag{10}$$

$$w_{\mathrm{S}} = \frac{\gamma \times A_{\mathrm{r_S}} \times 100}{M_{\mathrm{rf}}} \quad (11)$$

$$w_{\mathrm{N}} = \frac{\delta \times A_{\mathrm{r_N}} \times 100}{M_{\mathrm{rf}}} \quad (12)$$

$$w_{\mathrm{O}} = \frac{\varepsilon \times A_{\mathrm{r_O}} \times 100}{M_{\mathrm{rf}}} \quad (13)$$

with the molecular weight of an average fuel molecule $C_{\beta}H_{\alpha}S_{\gamma}N_{\delta}O_{\varepsilon}$ defined as:

$$M_{\mathrm{rf}} = \alpha \times A_{\mathrm{r_H}} + \beta \times A_{\mathrm{r_C}} + \gamma \times A_{\mathrm{r_S}} + \delta \times A_{\mathrm{r_N}} + \varepsilon \times A_{\mathrm{r_O}} \quad (14)$$

The fuel specific constant k_{f} is calculated using the following equation:

$$k_{\mathrm{f}} = 0.055584 \times w_{\mathrm{H}} - 0.0001083 \times w_{\mathrm{C}} - 0.0001562 \times w_{\mathrm{S}} + 0.0079936 \times w_{\mathrm{N}} + 0.0069978 \times w_{\mathrm{O}} \quad (15)$$

8.2 Step 2 – Atmospheric parameters

The absolute temperature, T_{a}, of the engine intake air, expressed in kelvin, and the dry atmospheric pressure, p_{s}, expressed in kilopascal, should be measured and recorded, and the parameter f_{a} calculated, which is defined for turbocharged compression ignition engines with or without cooling of the intake air as:

$$f_{\mathrm{a}} = \left(\frac{99}{p_{\mathrm{s}}}\right)^{0.7} \times \left(\frac{T_{\mathrm{a}}}{298}\right)^{1.5} \quad (16)$$

The f_{a} values should be stated with the results of the tests as it is a measure of how far from standard conditions the real test conditions were.

The following ambient parameters should be measured and recorded in the units given in Table 18:

- absolute humidity of the intake air (Ha) in mbar
- total barometric pressure (pb) in mbar.

Calculation of the saturation vapour pressure p_{a} [Pa] as a function of the temperature t [K] is calculated according to the Federal Register (40 CFR 1065 Part 645) equation:

$$\begin{aligned} p_{\mathrm{a}} = \exp(&-12.150799 \times \mathrm{In}(t) - 8{,}499.22 \times t^{-2} - 7423.1865 \times t^{-1} \\ &+ 96.1635147 + 0.024917646 \times t \\ &- 1.3160119 \times 10^{-5} \times t^{2} \\ &- 1.1460454 \times 10^{-8} \times t^{3} \\ &+ 2.1701289 \times 10^{-11} \times t^{4} \\ &- 3.610258 \times 10^{-15} \times t^{5} \\ &+ 3.8504519 \times 10^{-18} \times t^{6} - 1.4317 \times 10^{-21} \times t^{7}) \end{aligned} \quad (17)$$

This simpler formula leads to equivalent results:

$$p_{\mathrm{a}} = (4.856884 + 0.2660889 \times (t - 273.15) + 0.01688919 \times (t - 273.15)^2 - 7.477123 \times 10^{-5} \times (t - 273.15)^3 + 8.10525 \times 10^{-6} \times (t - 273.15)^4 - 3.115221 \times 10^{-8} \times (t - 273.15)^5) \times \frac{1013.2}{760} \times 100 \tag{18}$$

As the NOx emissions are highly dependent on ambient air conditions, the NOx concentration should be corrected for ambient air temperature and humidity with the factor $k_{\mathrm{h,D}}$ given in the following equation for diesel engines. This factor is valid for a humidity range between 0 and 25 g H_2O/kg dry air.

$$k_{\mathrm{h,D}} = \frac{15.698 \times H_{\mathrm{a}}}{1{,}000} + 0.832 \tag{19}$$

where:

H_a = humidity of the intake air [g H_2O/kg dry air].

Alternatively, the following formula may be applied to consider the impact of the ambient air temperature as well.

$$k_{\mathrm{h,D}} = \frac{1}{1 - 0.0182 \times (H_{\mathrm{a}} - 10.71) + 0.0045 \times (T_{\mathrm{a}} - 298)} \tag{20}$$

where:

H_a = humidity of the intake air [g H_2O/kg dry air]

T_a = ambient air temperature [K].

H_a and H_d can be derived from relative humidity measurement, dewpoint measurement, vapor pressure measurement or dry/wet bulb measurement using these generally accepted equations:

$$H_{\mathrm{a}} = \frac{621.8 \times \frac{\emptyset_{\mathrm{a}}}{100} \times p_{\mathrm{a}}}{p_{\mathrm{b}} - p_{\mathrm{a}} \times \frac{\emptyset_{\mathrm{a}}}{100}} \tag{21}$$

$$H_{\mathrm{d}} = \frac{621.8 \times \frac{RH_{\mathrm{d}}}{100} \times p_{\mathrm{d}}}{p_{\mathrm{b}} - p_{\mathrm{a}} \times \frac{RH_{\mathrm{d}}}{100}} \tag{22}$$

where:

$\emptyset_a$ = the relative humidity.

The density of the of the individual gas components ρ_{gas} can be calculated by:

$$\rho_{\text{gas}} = \frac{M_{\text{gas}}}{22.414} \qquad (23)$$

where:

M_{gas} = molar mass of the gas component mass [g/mol]

22.414 = Avogadro's constant [l/mol].

The relative molecular mass of the ambient air can be calculated from the density of the of the individual gas components and can be calculated by the following equation:

$$M_{\text{r air}} = \sum M_{\text{gas}} \times x_{\text{gas}} \qquad (24)$$

where:

M_{gas} = molar mass of the gas component mass [g/mol]

x_{gas} = molar fraction of the gas component mass (relative abundance) [-].

8.3 Step 3 – Intake air composition

The measured volumetric concentration of oxygen x_{O2} can be converted to mass fraction w_{O2} using the following equation:

$$w_{\text{ox}} = \frac{M_{\text{r O2}} \times x_{\text{O2}}}{M_{\text{r air}}} \qquad (25)$$

The mass fraction of inert air content can be calculated by:

$$w_{\text{inert}} = 1 - w_{\text{ox}} \qquad (26)$$

8.4 Step 4 – Calculation of stoichiometric air demand and additional volume from combustion

The total additional exhaust volume from combustion can be calculated with fuel specific constants: f_{fw} [m^3 volume change from combustion air to wet exhaust per kg fuel] and the corresponding value f_{fd} for the dry exhaust and are also further used to calculate the dry to wet correction factor and the exhaust densities (see Steps 8 and 9). f_{fw} can be calculated by adding up the additional volumes of the combustion of the fuel elements which can be simplified to:

$$f_{\text{fw}} = 0.055594 \times w_{\text{H}} + 0.0080021 \times w_{\text{N}} + 0.0070046 \times w_{\text{O}} \qquad (27)$$

The exhaust volume flow qv_{ew} can be calculated as follows:

$$q_{v_{\text{ew}}} = q_{v_{\text{aw}}} + q_{mf} \times f_{\text{fw}} \qquad (28)$$

f_{fw} is also used for calculation of wet exhaust density ρ_{ew} and dry/wet factor $k_{w,r}$.

The factor f_{fd} can be used for the calculation of the dry exhaust volume flow in this way:

$$q_{v\mathrm{ed}} = q_{v\mathrm{ad}} + f_{\mathrm{fd}} \times q_{m\mathrm{f}} \tag{29}$$

f_{fd} values are always negative which aligns with the volume of dry exhaust always being less than the volume of the intake air. The factor f_{fd} can be calculated from f_{fw} in this way:

$$f_{\mathrm{fd}} = f_{\mathrm{fw}} - \frac{w_{\mathrm{H}} \times V_{\mathrm{m_{H2O}}}}{200 \times A_{\mathrm{r_H}}} = f_{\mathrm{fw}} - w_{\mathrm{H}} \times 0.11118 \tag{30}$$

$$f_{\mathrm{fd}} = -0.055586 \times w_{\mathrm{H}} + 0.008002 \times w_{\mathrm{N}} + 0.0070046 \times w_{\mathrm{O}} \tag{31}$$

The minimum mass of air used during combustion (based on oxygen consumed in the combustion reactions) is known as the stoichiometric air demand or stoichiometric air to fuel ratio (A/F_{st}). However, in real diesel engines more air passes through the engine than is involved in combustion, at higher engine power outputs typically just under half the air that passes through the engine is involved in combustion but at low engine power (e.g. idle) under a tenth of the air is. The difference between stoichiometric and actual air to fuel ratios can vary significantly between different operating conditions so measurement and calculation accuracy is important and especially for Method 3. With the standard combustion reactions for the elements contained in a fuel, the stoichiometric air demand (the mass of air needed for combustion of 1 kg fuel) can be given as follows in a simpler easier to use form:

$$A/F_{\mathrm{st}} = \left(\frac{w_{\mathrm{C}}}{A_{\mathrm{r_C}}} + \frac{w_{\mathrm{H}}}{4 \times A_{\mathrm{r_H}}} + \frac{w_{\mathrm{S}}}{A_{\mathrm{r_S}}} - \frac{w_{\mathrm{O}}}{2 \times A_{\mathrm{r_O}}}\right) \times \frac{M_{\mathrm{rO2}}}{w_{\mathrm{ox}}} \tag{32}$$

With the term $1/w_{ox}$ the required oxygen mass is converted to the required air mass, and so the inert components of the air are taken into account. Inserting actual values:

$$A/F_{\mathrm{st}} = \left(\frac{w_{\mathrm{C}}}{12.011} + \frac{w_{\mathrm{H}}}{4.03176} + \frac{w_{\mathrm{S}}}{32.06} - \frac{w_{\mathrm{O}}}{31.9988}\right) \times 1.382 \tag{33}$$

Or in a slightly more complex but more accurate form including combustion of all the minor fuel components by:

$$A/F_{\mathrm{st}} = \frac{138.0 \times \left(1 + \frac{\alpha}{4} - \frac{\varepsilon}{2} - \gamma\right)}{12.011 + 1.00794 \times \alpha + 15.9994 \times \varepsilon + 14.0067 \times \delta + 32.065 \times \gamma} \tag{34}$$

The second more accurate approach for calculating the stoichiometric air demand improves the accuracy of the calculation step by ~0.2% for current specification fuels with an overall impact on the accuracy of calculating the final output of g/kWh factors of 0.35-0.4%, this shows the value in trying to maintain as much accuracy as possible as with these calculations as inaccuracies tend to accumulate over the calculation steps rather than cancel each other out.

8.5 Step 5 – Input engine measured values

This step in the spreadsheet calculation involves inputting data measured during testing and the calculation of a number of parameters for the following calculation steps. This method of calculating the exhaust dry/wet factor $k_{w,r}$ is to be preferred for emission measurements without direct air flow measurements, because the $k_{w,r}$ calculation by simpler methods assumes stoichiometric combustion and data for q_{mad}.

The water content of the exhaust and the dry/wet factor $k_{w,r}$ is calculated from the exhaust composition and the water concentrations from various origins (in % units) and can be directly derived from the CO_2 and CO concentrations without taking into account the H/C ratio α (assuming β = 1) and that one water molecule contains two hydrogen atoms. For the hydrogen content of the exhaust a subtraction has to be made, because from that corresponding hydrogen part of the fuel no water has been formed during combustion. Furthermore, the water in the intake air and the water still present after the gas cooling in the emissions measuring equipment have to be considered:

$$c_{\mathrm{H2O,combustion,d}} = 0.5 \times \alpha \times \left(c_{\mathrm{CO2d}} + \frac{c_{\mathrm{COd}}}{10^4}\right) - c_{\mathrm{H2d}} \qquad (35)$$

$$k_{\mathrm{w,r}} = \frac{q_{v\mathrm{ed}}}{q_{v\mathrm{ew}}} = \frac{q_{v\mathrm{ed}}}{q_{v\mathrm{ed}} + q_{v\mathrm{H2O,combustion,d}} + q_{v\mathrm{H2O,a}} - q_{v\mathrm{H2O,after\ cooler}}} \qquad (36)$$

where the concentration of H_2O, H_2 and CO_2 are expressed as a percentage and the concentration of CO is expressed in µmol/mol. Equation (34) can be rearranged into a more usable form in Equation (35) and Equation (36) and a similar factor for the intake air dry/wet conversion, $k_{w,r2}$ can then also be calculated:

$$k_{\mathrm{w,r}} = \frac{1}{1 + \frac{q_{v\mathrm{H2O,combustion,d}}}{q_{v\mathrm{ed}}} + \frac{q_{v\mathrm{H2O,ad}}}{q_{v\mathrm{ed}}} - \frac{q_{v\mathrm{H2O,after\ cooler}}}{q_{v\mathrm{ed}}}} \qquad (37)$$

$$k_{\mathrm{w,r}} = \frac{1}{1 + \frac{c_{\mathrm{H2O,combustion,d}}}{100} + \frac{c_{\mathrm{H2O,ad}}}{100} - \frac{c_{\mathrm{H2O,after\ cooler}}}{100}} \qquad (38)$$

$$k_{\mathrm{w,r2}} = \frac{1}{1 + \alpha \times 0.005 \times \left(c_{\mathrm{CO2d}} + \frac{c_{\mathrm{CO2d}}}{10{,}000}\right) - 0.01 \times c_{\mathrm{H2d}} + k_{\mathrm{w2}} - \frac{p_{\mathrm{r}}}{p_{\mathrm{b}}}} \qquad (39)$$

where:

k_{w2} = moisture in the intake air and is given by:

$$k_{\mathrm{w2}} = \frac{1.608 \times H_{\mathrm{a}}}{1{,}000 + (1.608 \times H_{\mathrm{a}})} \qquad (40)$$

H_a = humidity of the intake air [g water per kg of dry air]

c_{H2d} = concentration of hydrogen and is derived from the water gas equilibrium according to the following equation based on Society of Automotive Engineers (SAE) J 1088:

$$c_{\mathrm{H2d}} = \frac{0.5 \times \alpha \times \frac{c_{\mathrm{COd}}}{10^4} \times \left(\frac{c_{\mathrm{COd}}}{10^4} + c_{\mathrm{CO2d}}\right)}{\frac{c_{\mathrm{COd}}}{10^4} + 3 \times c_{\mathrm{CO2d}}} \quad (41)$$

Alternatively, if the intake air mass is measured flow is measured, $k_{w,r}$ can be calculated by:

$$k_{\mathrm{w,r}} = \frac{c_{\mathrm{gasw}}}{c_{\mathrm{gasd}}} = \frac{q_{v_{\mathrm{ed}}}}{q_{v_{\mathrm{ew}}}} = 1 - \frac{q_{v_{\mathrm{H2O}}}}{q_{v_{\mathrm{ew}}}} \quad (42)$$

or

$$k_{\mathrm{w}} = \left(1 - \frac{1.2442 \times H_{\mathrm{a}} + 111.19 \times \mathrm{w_H} \times \frac{q_{m\mathrm{f},i}}{q_{\mathrm{mad},i}}}{773.4 + 1.2442 \times H_{\mathrm{a}} + \frac{q_{m\mathrm{f},i}}{q_{\mathrm{mad},i}} \times k_{\mathrm{f}} \times 1{,}000}\right) \times 1.008 \quad (43)$$

or

$$k_{\mathrm{w}} = \left(1 - \frac{1.2442 \times H_{\mathrm{a}} + 111.19 \times \mathrm{w_H} \times \frac{q_{m\mathrm{f},i}}{q_{\mathrm{mad},i}}}{773.4 + 1.2442 \times H_{\mathrm{a}} + \frac{q_{m\mathrm{f},i}}{q_{\mathrm{mad},i}} \times k_{\mathrm{f}} \times 1{,}000}\right) \Big/ \left(1 - \frac{p_{\mathrm{r}}}{p_{\mathrm{b}}}\right) \quad (44)$$

or

$$k_{\mathrm{w,r}} = 1 - \frac{1.2442 \times H_{\mathrm{a}} + 111.187 \times \mathrm{w_H} \times \frac{q_{m\mathrm{f}}}{q_{m\mathrm{ad}}} - 773.4 \times \frac{p_r}{p_b}}{773.4 + 1.2442 \times H_{\mathrm{a}} + \frac{q_{m\mathrm{f}}}{q_{m\mathrm{ad}}} \times f_{\mathrm{fw}} \times 1{,}000} \quad (45)$$

where:

p_r = the water vapor pressure after cooling bath [kPa]

p_b = the total atmospheric pressure [kPa]

$q_{mf,i}$ = the instantaneous fuel flow rate [kg/s]

$q_{mad,i}$ = the instantaneous dry intake air flow rate [kg/s]

H_a = the intake air humidity [g water per kg dry air]

w_H = hydrogen content of the fuel [% mass]

k_f = the fuel specific factor [-] (see Step 1).

Note that Equations (43) and (51) are principally identical with the factor 1.008 in Equation (43) being an approximation for the more accurate denominator in Equation (51).

8.6 Step 6 – Calculation of excess air factor based on complete combustion

In diesel engines more air passes through the engine than is involved in combustion and is defined as excess air. The mass of excess air is defined using the ratio of the excess air to the stoichiometric air demand, with the ratio known as λ. The instantaneous excess air ratio λ_i is calculated by:

$$\lambda_i = \frac{\left(100 - \frac{c_{\mathrm{COd}} \times 10^{-4}}{2} - c_{\mathrm{HCw}} \times 10^{-4}\right) + \left(\frac{\alpha}{4} \times \frac{1 - \frac{2 \times c_{\mathrm{COd}} \times 10^{-4}}{3.5 \times c_{\mathrm{CO2d}}}}{1 + \frac{c_{\mathrm{COd}} \times 10^{-4}}{3.5 \times c_{\mathrm{CO2d}}}} - \frac{\varepsilon}{2} - \frac{\delta}{2}\right) \times (c_{\mathrm{CO2d}} + c_{\mathrm{COd}} \times 10^{-4})}{4.764 \times \left(1 + \frac{\alpha}{4} - \frac{\varepsilon}{2} + \gamma\right) \times (c_{\mathrm{CO2d}} + c_{\mathrm{COd}} \times 10^{-4} + c_{\mathrm{HCw}} \times 10^{-4})} \quad (46)$$

where:

λ_i = instantaneous excess air ratio [–]

c_{COd} = concentration of CO in the raw exhaust gas on a dry basis [µmol/mol]

c_{CO2d} = concentration of CO_2 in the raw exhaust gas on a dry basis [%]

c_{HCw} = concentration of HC in the raw exhaust gas on a wet basis [µmol/mol C1]

α = molar hydrogen-to-carbon ratio [–]

δ = molar nitrogen-to-carbon ratio [–]

ε = molar oxygen-to-carbon ratio [–]

γ = atomic sulphur-to-carbon ratio [–].

8.7 Step 7 – Excess air factor based on the US Federal Register § 86.345-79 procedure

For Method 1 (air and fuel measurement) which is most likely to be used with dynamometer-based testing where the intake air mass flow rate and fuel mass flow rate can be easily measured, the following equation allows calculation of the instantaneous exhaust mass flow using A/F_{st} and λ_i.

$$q_{mew,i} = q_{maw,i} \times \left(1 + \frac{1}{A/F_{\mathrm{st}} \times \lambda_i}\right) \quad (47)$$

Direct overall air-to-fuel ratios (equivalent to $A/F_{\mathrm{st}} \times \lambda_i$) are also usually measured by sensors in more modern engines (lambda / oxygen sensors, which are needed to monitor and control emissions abatement systems e.g. DPF regeneration) or by oxygen sensors in emissions measuring equipment. If this data are available it can be used to compare to actual and calculated *A/F* ratios with typically less than 1% variance if everything is done as accurately as possible.

8.8 Step 8 – Excess air and oxygen balance

Compared to the carbon balance method, the oxygen balance method gives slightly higher deviations compared to actual measured exhaust mass flows (up to 1% compared to 0.2% for the carbon balance method). Therefore, the carbon balance method should be the preferred method. However, the oxygen balance method can be used as an independent check of the other methods.

The following formula can be used for the calculation of the exhaust mass flow using the oxygen balance method.

$$q_{med} = q_{mf} \times \left[\frac{\left(1 - \frac{w_{\mathrm{H}}}{100} \times \frac{M_{\mathrm{rH2O}}}{2 \times A_{\mathrm{rH}}}\right) \times w_{\mathrm{ox}} \times 10 + 10 \times f_2 - 10}{w_{\mathrm{ox}} \times 10 - \frac{f_1}{1{,}000 \times \rho_{\mathrm{ed}}}} \right. \quad (48)$$

which transforms to the following equation upon substitution:

$$q_{med} = q_{mf} \times \frac{(1 - 0.08936 \times w_{\mathrm{H}}) \times w_{\mathrm{ox}} + f_2 - w_{\mathrm{O}}}{w_{\mathrm{ox}} - \frac{f_1}{10{,}000 \times \rho_{\mathrm{ed}}}} \quad (49)$$

$$q_{mew} = q_{mad} \times \left(1 + \frac{H_{\mathrm{a}}}{1{,}000}\right) + q_{mf} \quad (50)$$

f_1 and f_2 used in Equations (48) and (49) are defined as:

$$f_1 = \left(10{,}000 \times \frac{M_{\mathrm{rO2}} \times c_{\mathrm{CO2d}}}{V_{\mathrm{mO2}}} - \frac{A_{\mathrm{rO}}}{V_{\mathrm{mCO}}} \times c_{\mathrm{COd}}\right) \times \frac{1}{1 - \frac{p_{\mathrm{r}}}{p_{\mathrm{b}}}} + \frac{\left(\frac{A_{\mathrm{rO}}}{V_{\mathrm{mNO}}} \times c_{\mathrm{NOw}} + \frac{2 \times A_{\mathrm{rO}}}{V_{\mathrm{mNO2}}} \times c_{\mathrm{NO2w}} - \frac{3 \times A_{\mathrm{rO}}}{V_{\mathrm{mHC}}} \times c_{\mathrm{HCw}} - \frac{2}{}\right.}{k_{\mathrm{wr}}} \quad (51)$$

and

$$f_2 = w_{\mathrm{H}} \times \frac{A_{\mathrm{rO}}}{2 \times A_{\mathrm{rH}}} + w_{\mathrm{C}} \times \frac{2 \times A_{\mathrm{rO}}}{A_{\mathrm{rC}}} + w_{\mathrm{S}} \times \frac{2 \times A_{\mathrm{rO}}}{A_{\mathrm{rS}}} \quad (52)$$

Insertion of actual values:

$$f_1 = \frac{14{,}276 \times c_{\mathrm{O2d}} - 0.7138 \times c_{\mathrm{COd}}}{1 - \frac{p_{\mathrm{r}}}{p_{\mathrm{b}}}} + \frac{0.7138 \times c_{\mathrm{NOw}} + 1.4276 \times c_{\mathrm{NO2w}} - 2.1414 \times c_{\mathrm{HCw}} - 2.6641 \times c_{\mathrm{Cw}}}{k_{\mathrm{wr}}} \quad (53)$$

f_1 can be simplified assuming complete combustion:

$$f_{1\text{complete}} = \frac{\left(10{,}000 \times \frac{M_{\text{rO2}}}{V_{\text{mO2}}} \times c_{\text{O2d}}\right)}{\left(\frac{1}{1 - \frac{p_{\text{r}}}{p_{\text{b}}}}\right)} \tag{54}$$

with simplification for complete combustion and insertion of actual values:

$$f_1 = \frac{14{,}276 \times c_{\text{O2d}}}{1 - \frac{p_{\text{r}}}{p_{\text{h}}}} \tag{55}$$

$$f_2 = w_{\text{H}} \times 7.9367 + w_{\text{C}} \times 2.6641 + w_{\text{S}} \times 0.09979 \tag{56}$$

8.9 Step 9 – Calculation of exhaust mass flow

The key equation underlying all of the metrics is the mass flow balance is:

$$q_{mew,i} = q_{maw,i} + q_{mf,i} \tag{57}$$

where:

q_{maw} = Intake air mass flow rate on wet basis [kg/s]

q_{mew} = Exhaust gas mass flow rate on wet basis [kg/s]

q_{mf} = Fuel mass flow rate [kg/s].

For Method 3, the carbon and oxygen balance method is used for the calculation of the exhaust mass flow, in order to enable emission calculations without measurement of air flow or exhaust flow. The fuel consumption, fuel composition and concentration of the exhaust components all need to be known. It is only applicable for fuels containing C, H, S, N and O in known proportions.

The most accurate approach uses a set of iterative calculation steps but there is also a slightly less accurate alternative without iteration steps. The calculation of q_{med}, needs the values of ρ_{ed} and $k_{w,r}$, which are themselves dependent on q_{mad} and thus on the result of the q_{med} calculation. Therefore, an iterative (multi-step iteration) calculation procedure has to be applied. With preliminary starting values assumed for ρ_{ed} and $k_{w,r}$ (e.g. 1.34 kg/m^3 and 1) the q_{med} values are calculated, from these the q_{mad} values and from these ρ_{ed} and $k_{w,r}$. With these almost exact values ρ_{ed} and $k_{w,r}$ values in the next iteration step using the same formulae all data are exact enough, so that a third iteration step is not likely to be necessary to improve accuracy.

The following equations can be used for the calculation of the exhaust mass flow on the basis of the carbon balance method:

$$q_{med} = \frac{q_{mf} \times w_{C} \times \rho_{ed} \times 10^{4}}{A_{rC} \times \left(\left(\frac{(c_{CO2d} - c_{CO2,a}) \times 10^{4}}{V_{mCO2}} + \frac{c_{COd}}{V_{mCO}} \right) \times \frac{1}{1 - \frac{p_{r}}{p_{b}}} + \left(\frac{c_{HCw}}{V_{mHC}} + \frac{c_{Cw}}{A_{rC}} \right) \times \frac{1}{k_{wr}} \right)} \quad (58)$$

$$q_{mad} = q_{med} - q_{mf} \times \left(1 - \frac{w_{H}}{100} \times \frac{M_{rH2O}}{2 \times A_{rH}} \right) = q_{med} - q_{mf} \times (1 - w_{H} \times 0.08936) \quad (59)$$

$$q_{mew} = q_{mad} \times \left(1 + \frac{H_{a}}{1{,}000} \right) + q_{mf} \quad (60)$$

and for complete combustion:

$$q_{med} = q_{mf} \times \frac{\rho_{ed} \times 1.8663}{(c_{CO2d} - c_{CO2,a})} \quad (61)$$

Combining Equations (59), (60) and (61) in one equation and using some simplifications (neglecting unburned soot and assuming a fixed cooler temperature of 4°C, i.e. $1/(1 - p_r/p_b) = 1.008$), results in the following easier to use formula for the wet exhaust mass flow:

$$q_{mew} = q_{mf} \times \left(\left(\left(\frac{w_{C} + \rho_{ed}}{(c_{CO2d} - c_{CO2,a}) \times 0.540 + \frac{c_{COd} + \frac{c_{HCw}}{k_{wr}}}{10{,}000} \times 0.} + w_{H} \times 0.08936 - 1 \right) \times \left(1 + \frac{H_{a}}{1{,}000} \right) \right) + 1 \right) \quad (62)$$

A simpler and easier to use alternative to the multi-step iterative calculation procedure involves combining the two iteration steps in the final equation for the exhaust mass flow, thus enabling a single-step non-iterative calculation. The results of the single-step procedure are within ±0.2% of the multi-step procedure. The following one-step equation can be used for the calculation of the wet exhaust mass flow:

$$q_{mew} = q_{mf} \times \left(\left(\left(\frac{w_{C} + \rho_{ed}}{(c_{CO2d} - c_{CO2,a}) \times 0.540 + \frac{c_{COd} + \frac{c_{HCw}}{k_{wr}}}{10{,}000} \times 0.} + w_{H} \times 0.08936 - 1 \right) \times \left(1 + \frac{H_{a}}{1{,}000}\right) \right) + 1 \right) \quad (63)$$

Or alternatively in an easier to use form:

$$q_{mew} = q_{mf} \times \left(\left(\left(\frac{w_{C} + w_{C} \times 1.4}{\frac{\left(\frac{1.4 \times w_{C}}{f_{c}} + w_{H} \times 0.08936 - 1\right) \times \frac{1}{1.293} \times f}{f_{c} \times f_{c}}} + w_{H} \times 0.08936 - 1 \right) \times \left(1 + \frac{H_{a}}{1{,}000}\right) \right) + 1 \right) \quad (64)$$

with the carbon factor f_{c} given by:

$$f_{c} = (c_{CO2d} - c_{CO2,a}) \times 0.5441 + \frac{c_{COd}}{18{,}522} \times \frac{c_{HCw}}{17{,}355} \quad (65)$$

or the following simpler formula can also be used with the same precision:

$$q_{mew} = q_{mf} \times \frac{w_{C} \times w_{C} \times 1.4}{(1.0828 \times w_{C} + f_{fd} \times f_{c}) \times f_{c}} \times \left(1 + \frac{H_{a}}{1{,}000}\right) + 1 \quad (66)$$

For all methods, the exhaust densities (on both a wet and dry basis) are needed for future calculation steps and are calculated as outlined below. The exhaust density on a dry basis is calculated by dividing the exhaust mass flow by the exhaust volume flow:

$$\rho_{ed} = \frac{q_{med}}{q_{v_{ed}}} = \frac{q_{mad} + q_{mf} \times \left(1 - \frac{w_{H}}{100} \times \frac{M_{rH2O}}{2 \times A_{r_{H}}}\right)}{q_{v_{ad}} + f_{fd} \times q_{mf}} + 1 \quad (67)$$

$$\rho_{ed} = \frac{q_{mad} + q_{mf} \times \left(1 - \frac{w_{H}}{100} \times \frac{M_{r_{H2O}}}{2 \times A_{r_{H}}}\right)}{\frac{q_{mad}}{1.293} + f_{fd} \times q_{mf}} = \frac{q_{mad} + q_{mf} \times (1 - w_{H} \times 0.08936)}{\frac{q_{mad}}{1.293} + f_{fd} \times q_{mf}} \quad (68)$$

Similarly, the exhaust density on a wet basis ρ_{ew} can be calculated as follows:

$$\rho_{\mathrm{ew}} = \frac{q_{mew}}{q_{v\,\mathrm{ew}}} = \frac{q_{maw} + q_{mf}}{q_{v\,\mathrm{aw}} + f_{\mathrm{fw}} \times q_{mf}} \tag{69}$$

$$\rho_{\mathrm{ew}} = \frac{q_{mad} + \frac{H_{\mathrm{a}} \times q_{mad}}{1{,}000} \times q_{mf}}{\frac{q_{mad}}{1{,}293} + \frac{q_{mad} \times H_{\mathrm{a}} \times V_{\mathrm{mH2O}}}{1{,}000 \times M_{\mathrm{rH2O}}} + f_{\mathrm{fw}} \times q_{mf}} \tag{70}$$

$$\rho_{\mathrm{ew}} = \frac{1{,}000 + H_{\mathrm{a}} + 1{,}000 \times \frac{q_{mf}}{q_{mad}}}{773.4 + 1.2434 \times H_{\mathrm{a}} + 1{,}000 \times f_{\mathrm{fw}} \times \frac{q_{mf}}{q_{mad}}} \tag{71}$$

8.10 Step 10 – Dry to wet conversions

Dry concentrations should be converted to wet concentrations using the following equation:

$$c_{\mathrm{w}} = k_{\mathrm{w}} + c_{\mathrm{d}} \tag{72}$$

except for NOx with the additional humidity correction factor $k_{h,d}$ calculated in Step 2:

$$c_{\mathrm{w}} = k_{\mathrm{w}} \times k_{\mathrm{h,d}} \times c_{d} \tag{73}$$

where:

c_w = the wet concentration of an individual gas

c_d = the dry concentration of an individual gas

k_w = dry to wet conversion factor [-]

$k_{h,d}$ = the NOx correction for humidity and temperature [-].

8.11 Step 11 – Calculation of dry hydrocarbon concentration

If desired, hydrocarbon wet to dry concentrations can be converted using the following equation similar to that used in Step 10:

$$c_{\mathrm{d}} = \frac{c_{\mathrm{w}}}{k_{\mathrm{w}}} \tag{74}$$

8.12 Step 12 – Calculation of ratio of density of exhaust component to density of exhaust gas

The mass of emissions should be calculated using Equation (79) in Step 13. Instead of using the generalised default tabulated values, the following equations should be applied for the calculation of u_{gas}. It is assumed in the following equations that the concentration c_{gas} in Equation (79) is measured in or converted to µmol/mol.

$$u_{\text{gas},i} = \frac{M_{\text{gas}}}{M_{\text{e},i} \times 1000} \qquad (75)$$

or

$$u_{\text{gas},i} = \frac{\rho_{\text{gas}}}{\rho_{\text{e},i} \times 1000} \qquad (76)$$

where:

M_{gas} = molar mass of the gas component [g/mol]

$M_{\text{e},i}$ = instantaneous molar mass of the wet raw exhaust gas [g/mol]

ρ_{gas} = density of the individual gas component [kg/m^3] which is M_{gas}/22.414

$\rho_{\text{e},i}$ = instantaneous density of the wet raw exhaust gas [kg/m^3].

The densities, ρ_{gas}, are given for a number of exhaust gas components in Table 17. The molecular mass of the exhaust, M_{e}, should be derived for a general fuel composition $C_{\beta}H_{\alpha}O_{\varepsilon}N_{\delta}S_{\gamma}$ under the assumption of complete combustion, as follows:

$$M_{\text{e},i} = \frac{1 + \frac{q_{m\text{f},i}}{q_{maw,i}}}{\frac{q_{m\text{f},i}}{q_{maw,i}} \times \frac{\frac{\alpha}{4} + \frac{\varepsilon}{2} + \frac{\delta}{2}}{12.001 + 1.00794 \times \alpha + 15.9994 \times \varepsilon + 14.0067 \times \delta + 32.0065 \times \gamma} + \frac{\frac{H_{\text{a}} \times 10^{-3}}{2 \times 1.00794 + 15.9994} + \frac{1}{M_{\text{r,air}}}}{1 + H_{\text{a}} \times 10^{-3}}} \qquad ($$

8.13 Step 13 – Calculation of gas component mass flow

The emission rate of a gaseous emission $q_{mgas,i}$ for each mode i of the steady state test should be calculated. The concentration of the gaseous emission should be multiplied by its respective flow:

$$q_{mgas,\text{i}} = k \times u_{\text{gas}} \times q_{mew,i} \times c_{\text{gas},i} \times 3{,}600 \qquad (78)$$

where:

q_{mgas} = the emission mass flow rate of individual gas

k = a unit conversion factor which equals 1 for $c_{\text{gas},i}$ in [µmol/mol] and 10,000 for $c_{\text{gas},i}$ in [% vol]

u_{gas} = the ratio between density of exhaust component and density of exhaust gas

c_{gas} = the concentration of the respective component in the raw exhaust gas [µmol/mol or ppm]

q_{mew} = the exhaust mass flow [kg/s].

The measured concentration should be converted to a wet basis according to Step 10, if not already measured on a wet basis. Values for u are calculated in Step 12.

8.14 Step 14 – Calculation of g/m³ factors

The mass of a gaseous emission component per unit volume of exhaust [g/m³ factors] for each mode *i* of the test can be calculated using the rate of a gaseous emission $q_{mgas,i}$ from Step 13 and exhaust mass flow and density from Step 9:

$$c_{mgas,i} = \frac{q_{mgas,i}}{\left(\frac{q_{mew,i}}{\rho_{ew,i}}\right)} \tag{79}$$

8.15 Step 15 – Calculation of g/kWh factors

The specific emissions $e_{gas,i}$ [g/kWh factors] for each test mode are calculated using this equation:

$$e_{gas,i} = \frac{m_{gas,i}}{W_{act,i}} \tag{80}$$

where:

m_{gas} = total mass of emission [g/test]

W_{act} = cycle work including auxiliary loads [kWh].

8.16 Step 16 – Calculation of single weighted g/kWh factors

For current European non-road mobile machinery (NRMM) emission standards (which apply to rail) and previous European road emission standards, weighting of the regulatory drive cycle to derive a single e_{gas} [g/kWh factors] is based on:

$$e_{gas} = \frac{\sum_{i=1}^{n_{mode}} (q_{mgas,i} \times f_{WFi})}{\sum_{i=1}^{n_{mode}} (P_i \times f_{WFi})} \tag{81}$$

where:

$q_{mgas,i}$ = mean emission mass flow rate for the mode *i* [g/h]

n_{mode} = the number of modes

P_i = engine power for the mode *i* [kW] with $P_i = P_{m,i} + P_{aux,i}$

$f_{WF,i}$ = weighting factor for the mode *i* [–].

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

The US approach is different in that it gives a weighting based on the relative time in each notch and is unbiased by the power produced in each mode and hence does not bias in favour of emissions under high power modes and disfavour emissions under low power modes as the ISO method does. The US Rail approach calculates a single emission factor using:

$$e_{\text{gas}} = \sum_{i=1}^{n_{mode}} e_{\text{gas,i}} \times f_{\text{WF}i} \tag{82}$$

The US mathematical weighting approach ultimately requires emission reductions for all parts of the drive cycle, rather than just emissions reductions for certain (typically higher) power outputs which may be relatively easier to achieve.

8.17 Step 17 – Calculating particulate emissions

8.17.1 General background to particulate mass emissions

The determination of the particulate emissions typically requires a dilution system, unlike gaseous emission concentrations or particle number (PN) that can be measured on either a raw (preferred) or dilute basis. This step involves using the exhaust mass flow rate q_{me} calculated in Step 11 for gaseous emissions and combining it with particulate measurement data.

Until relatively recently, particulates were measured by the gravimetric balance method, i.e. by weighing the mass of a filter before and after a test or test mode to determine the change in mass due to the collection of particulate matter. More recently emissions testing equipment manufacturers have developed equipment that allows continuous real time particulate measurements on a second-by-second basis in a similar manner to that for gaseous emissions, however the continuous PM measurements should still be calibrated to the PM measured by gravimetric balance method over the entire set of tests (with the continuous PM PEMS equipment having a filter holder to enable this calibration).

The flow capacity of the dilution system should be large enough to completely eliminate water condensation in the dilution and sampling systems and to maintain the temperature of the diluted exhaust gas between 42°C and 52°C immediately upstream of the filter holders. Dehumidifying the dilution air before entering the dilution system is permitted, and especially useful if dilution air humidity is high. The temperature of the dilution air should be between 20°C and 52°C in close proximity to the entrance into the dilution tunnel.

A partial flow dilution system should be designed to extract a proportional raw exhaust sample from the engine exhaust stream, thus responding to variations in the exhaust stream flow rate, and introduce dilution air to this sample to achieve a temperature between 42°C and 52°C at the test filter. For this it is essential that the dilution ratio or the sampling ratio r_d or r_s be determined such that the accuracy limits are fulfilled. Different extraction methods can be applied, whereby the type of extraction used dictates to a significant degree the sampling hardware and procedures to be used.

To determine the mass of the particulates using the gravimetric balance method, a particulate sampling system, particulate sampling filters, a microgram balance and a temperature and humidity-controlled weighing chamber are required. The details are described in ISO 8178-1:2020, 8.1. The tare weight of the filter should be subtracted from the gross weight of the filter, which results in the particulate sample mass (m_f). For the evaluation of the particulate concentration, the total sample mass (m_{sep}) through the filters over the test cycle should be recorded.

In general, the particulate sampling probe should be installed in close proximity to the gaseous emissions sampling probe, but sufficiently distant as to not cause interference. The sampling line should conform to the requirements of ISO 8178-1:2020, 7.4.2. The particulate mass may be corrected for the particulate level of the dilution air.

8.17.2 Calculation of PM emissions for partial flow dilution systems

The particulate emission over the cycle m_{PM} [g] based on sample ratio should be calculated with this equation:

$$m_{\mathrm{PM}} = \frac{m_{\mathrm{f}}}{r_{\mathrm{s}} \times 1000} \tag{83}$$

where:

m_f = particulate mass sampled over the cycle [mg]

r_s = average sample ratio over the test cycle [−]

with:

$$r_{\mathrm{s}} = \frac{m_{\mathrm{se}}}{m_{\mathrm{ew}}} \times \frac{m_{\mathrm{sep}}}{m_{\mathrm{sed}}} \tag{84}$$

where:

m_{se} = sample mass of raw exhaust over the cycle [kg]

m_{ew} = total mass of raw exhaust over the cycle [kg]

m_{sep} = mass of diluted exhaust gas passing through the particulate collection filters [kg]

m_{sed} = mass of diluted exhaust gas passing the dilution tunnel [kg].

In the case of a total sampling type system, m_{sep} and m_{sed} are identical.

The particulate emission over the cycle m_{PM} [g] based on dilution ratio should be calculated with this equation:

$$m_{\mathrm{PM}} = \frac{m_{\mathrm{f}}}{m_{\mathrm{sep}}} \times \frac{m_{\mathrm{edf}}}{1000} \tag{85}$$

where:

m_f = particulate mass sampled over the cycle [mg]

m_{sep} = mass of diluted exhaust gas passing through the particulate collection filters [kg]

m_{edf} = mass of equivalent diluted exhaust gas over the cycle [kg].

The total mass of equivalent diluted exhaust gas mass over the cycle or test m_{edf} [kg] should be determined as follows:

$$m_{\mathrm{edf}} = \frac{1}{f} \sum_{i=1}^{n_{mode}} q_{m\mathrm{edf},i} \quad (86)$$

$$q_{m\mathrm{edf},i} = q_{m\mathrm{ewf},i} \times r_{\mathrm{di}} \quad (87)$$

$$r_{\mathrm{d},i} = \frac{q_{m\mathrm{dew},i}}{q_{m\mathrm{dew},i} - q_{m\mathrm{dw},i}} \quad (88)$$

where:

$q_{medf,i}$ = instantaneous equivalent diluted exhaust mass flow rate [kg/s]

$q_{mew,i}$ = instantaneous exhaust mass flow rate on a wet basis [kg/s]

$r_{d,i}$ = instantaneous dilution ratio [−]

$q_{mdew,i}$ = instantaneous diluted exhaust mass flow rate on a wet basis [kg/s]

$q_{mdw,i}$ = instantaneous dilution air mass flow rate [kg/s]

f = data sampling rate [Hz]

n = number of measurements [−].

8.17.3 Calculation of PM mass emissions for full flow dilution systems

The mass emission should be calculated in this way:

$$m_{\mathrm{PM}} = \frac{m_{\mathrm{f}}}{m_{\mathrm{sep}}} \times \frac{m_{\mathrm{ed}}}{1000} \quad (89)$$

where:

m_f = particulate mass sampled over the cycle [mg]

m_{sep} = mass of diluted exhaust gas passing the particulate collection filters [kg]

m_{ed} = mass of diluted exhaust gas over the cycle [kg]

with:

$$m_{\mathrm{sep}} = m_{\mathrm{set}} - m_{ssd} \quad (90)$$

where:

m_{set} = mass of double diluted exhaust gas through particulate filter [kg]

m_{ssd} = mass of secondary dilution air [kg].

8.17.4 Background PM level correction

The particulate mass $m_{PM,c}$ [g] may be background corrected in this way:

$$m_{\mathrm{PM},c} = \left\{\frac{m_\mathrm{f}}{m_\mathrm{sep}} - \left[\frac{m_\mathrm{b}}{m_\mathrm{sd}} \times \left(1 - \frac{1}{D}\right)\right]\right\} \times \frac{m_\mathrm{ed}}{1000} \quad (91)$$

where:

m_f = particulate mass sampled over the cycle [mg]

m_{sep} = mass of diluted exhaust gas passing the particulate collection filters [kg]

m_{sd} = mass of dilution air sampled by background particulate sampler [kg]

m_b = mass of collected background particulates of dilution air [mg]

m_{ed} = mass of diluted exhaust gas over the cycle [kg]

D = dilution factor [-] (see Equation (93) below).

The dilution factor D (which is necessary for the background correction calculation) should be calculated in this way for diesel fuelled engines:

$$D = \frac{F_\mathrm{S}}{c_\mathrm{CO2,e} + \left(c_\mathrm{HC,e} + c_\mathrm{CO,e}\right) \times 10^{-4}} \quad (92)$$

where:

F_S = stoichiometric factor [−]

$c_{CO2,e}$ = concentration of CO_2 in the diluted exhaust gas on a wet basis [% vol]

$c_{HC,e}$ = concentration of HC in the diluted exhaust gas on a wet basis [µmol/mol C1]

$c_{NMHC,e}$ = concentration of non-methane hydrocarbon (NMHC) in the diluted exhaust gas on a wet basis [µmol/mol C1]

$c_{CO,e}$ = concentration of CO in the diluted exhaust gas on a wet basis [µmol/mol].

The stoichiometric factor should be calculated in this way:

$$F_\mathrm{S} = 100 \times \frac{1}{1 + \frac{\alpha}{2} + 3.76 \times \left(1 + \frac{\alpha}{4}\right)} \quad (93)$$

where:

α = molar hydrogen to carbon ratio in the fuel [−].

If a direct measurement is made of the exhaust gas flow, the dilution factor D may be calculated in this way:

$$D = q_{v\mathrm{CVS}} + q_{v\mathrm{ew}} \quad (94)$$

where:

q_{vCVS} = the volumetric flow rate of diluted exhaust gas [m^3/s]

q_{vew} = the volumetric flow rate of raw exhaust gas [m^3/s].

The dilution air should have the same standardisation correction calculations applied as for the intake air environmental correction (Step 2):

$$k_{w,d} = (1 - k_{w3}) \times 1.008 \quad (95)$$

where:

$$k_{w3} = \frac{1{,}608 \times H_d}{1{,}000 + 1{,}608 \times H_d} \quad (96)$$

where:

H_d = dilution air humidity [g H_2O/kg dry air].

8.17.5 Calculation for steady-state discrete-mode cycles

All calculations should be based upon the average values of the individual modes during the sampling period.

For partial-flow dilution, the equivalent mass flow of diluted exhaust gas should be determined by:

$$q_{medf} = q_{mew} \times r_d \quad (97)$$

$$r_d = \frac{q_{mdew}}{q_{mdew} - q_{mdw}} \quad (98)$$

where:

q_{medf} = equivalent diluted exhaust mass flow rate [kg/s]

q_{mew} = exhaust mass flow rate on a wet basis [kg/s]

r_d = dilution ratio [−]

q_{mdew} = diluted exhaust mass flow rate on a wet basis [kg/s]

q_{mdw} = dilution air mass flow rate [kg/s].

For full-flow dilution systems q_{mdew} is used as q_{medf}.

For the single-filter method, the particulate emission flow rate over the cycle q_{mPM} [g/h] should be calculated in this way:

$$q_{mPM} = \frac{m_f}{m_{sep}} \times \overline{q_{medf}} \times \frac{3600}{1000} \quad (99)$$

$$\overline{q_{medf}} = \sum_{i=1}^{n_{mode}} q_{medfi} \times f_{WFi} \quad (100)$$

$$\overline{q_{medf}} = \sum_{i=1}^{n_{mode}} q_{medfi} \times f_{WFi} \tag{101}$$

where:

q_{mPM} = particulate mass flow rate [g/h]

m_f = particulate mass sampled over the cycle [mg]

q_{medf} = average equivalent diluted exhaust gas mass flow rate on wet basis [kg/s]

q_{medfi} = equivalent diluted exhaust gas mass flow rate on wet basis at mode *i* [kg/s]

f_{WFi} = weighting factor for the mode *i* [−]

m_{sep} = mass of diluted exhaust gas passing the particulate collection filters [kg]

m_{sepi} = mass of diluted exhaust sample passed through the particulate sampling filter at mode *i* [kg]

n = number of measurements [−].

For the multiple-filter and continuous sampling methods, the particulate emission flow rate over the cycle q_{mPMi} [g/h] should be calculated in this way:

$$q_{mPMi} = \frac{m_{fi}}{m_{sepi}} \times \overline{q_{medfi}} \times \frac{3600}{1000} \tag{102}$$

where:

q_{mPMi} = the particulate mass flow rate at mode *i* [g/h]

m_{fi} = the particulate sample mass corrected at mode *i* [mg]

q_{medfi} = the equivalent diluted exhaust gas mass flow rate on wet basis at mode *i* [kg/s]

m_{sepi} = the mass of diluted exhaust sample passed through the particulate sampling filter at mode *i* [kg].

The PM mass is determined over the test cycle by summation of the average values of the individual modes *i* during the sampling period.

The particulate mass flow rate q_{mPM} [g/h] may be background corrected for the single-filter method:

$$q_{mPM} = \left\{ \frac{m_f}{m_{sep}} - \left[\frac{m_{f,d}}{m_d} \times \sum_{i=1}^{n_{mode}} \left(1 - \frac{1}{D_i}\right) \times f_{WFi} \right] \right\} \times \overline{q_{medf}} \times \frac{3600}{1000} \tag{103}$$

And for multiple-filter and continuous methods:

$$q_{m\mathrm{PM}i} = \left\{ \frac{m_{\mathrm{f}i}}{m_{\mathrm{sep}i}} - \left[\frac{m_{\mathrm{f,d}}}{m_{\mathrm{d}}} \times \left(1 - \frac{1}{D} \right) \right] \right\} \times \overline{q_{m\mathrm{edf}i}} \times \frac{3600}{1000} \quad (104)$$

where:

$q_{m\mathrm{PM}}$ = the particulate mass flow rate [g/h]

$q_{m\mathrm{PM}i}$ = the particulate mass flow rate at mode *i* [g/h]

m_{f} = the particulate sample mass collected [mg]

$m_{\mathrm{f}i}$ = the particulate sample mass collected at mode *i* [mg]

m_{sep} = the mass of diluted exhaust sample passed through the particulate sampling filter [kg]

$m_{\mathrm{sep}i}$ = the mass of diluted exhaust sample passed through the particulate sampling filter at mode *i* [kg]

$m_{\mathrm{f,d}}$ = the particulate sample mass of the dilution air collected [mg]

m_{d} = the mass of the dilution air sample passed through the particulate sampling filters [kg]

D = the dilution factor [-] (see Equation (93))

D_i = the dilution factor at mode *i* [-]

$f_{\mathrm{WF}i}$ = the weighting factor for the mode *i* [−]

$q_{m\mathrm{edf}}$ = the average equivalent diluted exhaust gas mass flow rate on wet basis [kg/s]

$q_{m\mathrm{edf}i}$ = the equivalent diluted exhaust gas mass flow rate on wet basis at mode *i* [kg/s].

If more than one measurement is made then $m_{(\mathrm{f,d})}/m_{\mathrm{d}}$ should be replaced with $\overline{m_{\mathrm{f,d}}/m_{\mathrm{d}}}$.

The particulate specific emissions should be calculated with Equation (81) where e_{gas} [g/kWh] and m_{gas} [g/test] are substituted by e_{PM} [g/kWh] and m_{PM} [g/test] respectively:

$$e_{\mathrm{PM}} = \frac{m_{\mathrm{PM}}}{W_{\mathrm{act}}} \quad (105)$$

where:

m_{PM} = total mass of particulate emissions [g/test]

W_{act} = cycle work [kWh].

8.17.6 Steady-state discrete-mode cycle emissions factors

For the single-filter method, the particulate specific emission e_{PM} [g/kWh] should be calculated in this way:

$$e_{\mathrm{PM}} = \frac{q_{m\mathrm{PM}}}{\sum_{i=1}^{n_{mode}} (P_i \times f_{\mathrm{WF}i})} \tag{106}$$

where:

P_i = engine power for the mode i [kW] with $P_i = P_{m,i} + P_{aux,i}$

f_{WFi} = weighting factor for the mode i [−]

q_{mPM} = particulate mass flow rate [g/h].

For the multiple-filter and continuous sampling methods, the particulate specific emission e_{PM} [g/kWh] should be calculated in this way:

$$e_{\mathrm{PM}} = \frac{\sum_{i=1}^{n_{mode}} (q_{m\mathrm{PM}} \times f_{\mathrm{WF}i})}{\sum_{i=1}^{n_{mode}} (P_i \times f_{\mathrm{WF}i})} \tag{107}$$

where:

P_i = engine power for the mode i [kW] with $P_i = P_{m,i} + P_{aux,i}$

f_{WFi} = weighting factor for the mode i [−]

q_{mPMi} = particulate mass flow rate at mode i [g/h].

Effective weighting factor (steady-state discrete cycles only)

For the single-filter method, the effective weighting factor, f_{WFei}, for each mode should be calculated in this way:

$$f_{\mathrm{WFe}i} = \frac{m_{\mathrm{sep}i} \times \overline{q}_{m\mathrm{edf}}}{m_{\mathrm{sep}} \times q_{m\mathrm{edfi}}} \tag{108}$$

where:

q_{medf} = average equivalent diluted exhaust gas mass flow rate on wet basis [kg/s]

q_{medfi} = equivalent diluted exhaust gas mass flow rate on wet basis at mode i [kg/s]

m_{sep} = mass of diluted exhaust gas passing through the particulate collection filters [kg]

m_{sepi} = mass of diluted exhaust sample passed through the particulate sampling filter at mode i [kg].

8.18 Step 18 – Calculating particulate number (PN) emissions

Where particle numbers are sampled using a partial flow dilution or a raw gas sampling system, the number of particles emitted over the test cycle should be calculated by means of this equation:

$$N = \frac{m_{\mathrm{edf}}}{1.293} \times k \times \overline{c_s} \times \overline{f_r} \times 10^6 \tag{109}$$

where:

N = number of particles emitted over the test cycle [#/test]

m_{edf} = mass of equivalent diluted exhaust gas over the cycle if diluted or mew if not [kg/test]

k = calibration factor [-] to correct the particle number counter measurements to the level of the reference instrument where this is not applied internally within the particle number counter. Where the calibration factor is applied internally within the particle number counter, a value of 1 should be used for *k* in the above equation

$\overline{c_s}$ = average concentration of particles from the diluted exhaust gas corrected to standard conditions (273.15 K and 101.33 kPa) [#/cm^3]

$\overline{f_r}$ = mean particle concentration reduction factor [-] of the volatile particle remover specific to the dilution settings used for the test.

$\overline{c_s}$ should be calculated from the following equation:

$$\overline{c_s} = \frac{\sum_{i=1}^{n_{mode}} c_{\mathrm{s},i}}{n} \tag{110}$$

where:

$c_{\mathrm{s},i}$ = a discrete measurement of particle concentration in the diluted gas exhaust from the particle counter, corrected for coincidence and to standard conditions (273.15 K and 101.33 kPa) [#/cm^3]

n = number of particle concentration measurements taken over the duration of the test
[-].

8.18.1 Calculation of particle numbers with raw gas sampling systems

Where particle numbers are sampled using a raw gas sampling system, the number of particles emitted over the test cycle should be calculated by means of the following equation:

$$N = \frac{1}{f} \sum_{i=1}^{n_{mode}} \left(\frac{q_{\mathrm{mew}}}{\rho_{\mathrm{e},i}} \times \overline{c_s} \right) \times k \times \overline{f_r} \times 10^6 \tag{111}$$

where:

N	= the number of particles emitted over the test cycle [#/test]
$q_{mew,i}$	= the instantaneous exhaust gas flow rate on a wet basis [kg/s]
$\rho_{e,i}$	= the instantaneous density of the exhaust gas in the standard conditions 273.15 K and 101.33 kPa and on a wet basis [kg/m^3] (refer to Equation (72))
k	= the calibration factor [-] to correct the particle number counter measurements to the level of the reference instrument where this is not applied internally within the particle number counter. Where the calibration factor is applied internally within the particle number counter, a value of 1 should be used for k in the above equation.
f_r	= the mean particle concentration reduction factor of the volatile particle remover specific to the dilution settings used for the test [-]
$c_{s,i}$	= a discrete measurement of particle concentration in the raw exhaust gas from the particle counter, corrected for coincidence and to standard conditions (273.15 K and 101.33 kPa) [#/cm^3]
n	= the number of particle concentration measurements taken over the duration of the test [-]
f	= the data sampling rate [Hz].

8.18.2 Calculation of particle numbers with a full flow dilution system

Where particle numbers are sampled using a full flow dilution system, the number of particles emitted over the test cycle should be calculated by means of the following equation:

$$N = \frac{m_{\mathrm{ed}}}{1.293} \times k \times \overline{c_s} \times \overline{f_r} \times 10^6 \qquad (112)$$

where:

N	= number of particles emitted over the test cycle [#/test]
m_{ed}	= total diluted exhaust gas flow over the cycle [kg/test]
k	= calibration factor [-] to correct the particle number counter measurements to the level of the reference instrument where this is not applied internally within the particle number counter. Where the calibration factor is applied internally within the particle number counter, a value of 1 should be used for k in the above equation
c_s	= average corrected concentration of particles from the diluted exhaust gas corrected to standard conditions (273.15 K and 101.33 kPa) [#/cm^3]
f_r	= mean particle concentration reduction factor of the volatile particle remover specific to the dilution settings used for the test [-].

$\overline{c_s}$ should be calculated from Equation (111).

8.18.3 Calculation of particle numbers for discrete-mode cycles

Where particle numbers are sampled using a partial-flow dilution system, the particle emission rate during each individual discrete mode should be calculated by means of Equation (144) using average values for the mode:

$$\dot{N} = \frac{q_{\mathrm{medf}}}{\rho_{ew}} \times k \times \overline{c_s} \times \overline{f_r} \times 10^6 \times 3600 \qquad (113)$$

Where:

$\dot{N}$ = the rate of emission of particles during the individual discrete mode [#/h]

q_{medf} = the equivalent diluted exhaust mass flow rate on a wet basis during the individual discrete mode, determined according to Equation (88) [kg/s]

k = the calibration factor [-] to correct the particle number counter measurements to the level of the reference instrument where this is not applied internally within the particle number counter. Where the calibration factor is applied internally within the particle number counter, a value of 1 should be used for k in the above equation.

$\overline{c_s}$ = the average concentration of particles from the diluted exhaust gas during the individual discrete mode corrected to standard conditions (273.15 K and 101.33 kPa) [#/cm^3]

f_r = the mean particle concentration reduction factor of the volatile particle remover specific to the dilution settings used for the test [-].

With $\overline{c_s}$ calculated using Equation (111) but in this case with

n = the number of particle concentration measurements taken during the individual discrete mode sampling period.

Where particle numbers are sampled using a raw gas sampling system, the particle emission rate during each individual discrete mode should be calculated by means of the following equation using average values for the mode:

$$\dot{N} = \frac{q_{\mathrm{mew}}}{1.293} \times k \times \overline{c_s} \times \overline{f_{\mathrm{r}}} \times 10^6 \times 3600 \qquad (114)$$

where:

$\dot{N}$ = the rate of emission of particles during the individual discrete mode [#/h]

q_{mew} = the average exhaust gas flow rate on a wet basis during the individual discrete mode [kg/s]

k = the calibration factor [-] to correct the particle number counter measurements to the level of the reference instrument where this is not applied internally within the particle number counter, a value of 1 should be used for k in the above equation

ρ_e = the average density of the exhaust gas in the standard conditions 273.15 K and 101.33 kPa) and on a wet basis during the individual discrete mode [kg/m^3] (refer to Equations (35) and (36))

c_s = the average concentration of particles from the raw exhaust gas during the individual discrete mode corrected to standard condition (273.15 K and 101.33 kPa) [#/cm^3]

f_r = the mean particle concentration reduction factor of the volatile particle remover specific to the dilution settings used for the test [-]

with $\overline{c_s}$ calculated using Equation (111) but in this case with:

n = the number of particle concentration measurements taken during the individual discrete mode sampling period.

Where particle numbers are sampled using a full flow dilution system, the rate of emission of particles during each individual discrete mode should be calculated by means of the following equation using the average values for the mode:

$$\dot{N} = \frac{q_{\mathrm{mdew}}}{1.293} \times k \times \overline{c_{\mathrm{s}}} \times \overline{f_{\mathrm{r}}} \times 10^6 \times 3600 \quad (115)$$

where:

$\dot{N}$ = the rate of emission of particles during the individual discrete mode [#/h]

q_{mdew} = the total diluted exhaust mass flow rate on a wet basis during the individual discrete mode [kg/s]

k = the calibration factor [-] to correct the particle number counter measurements to the level of the reference instrument where this is not applied internally within the particle number counter. Where the calibration factor is applied internally within the particle number counter, a value of 1 should be used for k in the above equation.

c_s = the average concentration of particles from the diluted exhaust gas during the individual discrete mode corrected to standard conditions 273.15 K and 101.33 kPa) [#/cm^3]

f_r = the mean particle concentration reduction factor of the volatile particle remover specific to the dilution settings used for the test

with $\overline{c_s}$ calculated using Equation (111) but in this case with

n = the number of particle concentration measurements taken during the individual discrete mode sampling period.

8.18.4 Calculation of specific PN for mode or test results

The specific particle number emissions for each test mode in number of particles per kWh should be calculated in this way:

$$e_{\mathrm{PN}} = \frac{N}{W_{\mathrm{act}}} \tag{116}$$

where:

e_{PN} = the number of particles emitted [#/kWh]

N = number of particles emitted over the applicable time

W_{act} = the actual cycle work [kWh].

The specific emissions *e* [#/kWh] are calculated in this way:

$$e = \frac{\sum_{i=1}^{n_{mode}} \left(\dot{N}_i \times f_{\mathrm{WF}i}\right)}{\sum_{i=1}^{n_{mode}} \left(P_i \times f_{\mathrm{WF}i}\right)} \tag{117}$$

where:

P_i = the engine power for the mode *i* [kW] with Pi = $P_{m,i} + P_{\mathrm{aux},i}$

$f_{\mathrm{WF}i}$ = the weighting factor for the mode *i* [−]

$\dot{N}_i$ = the mean emission number flow rate for the mode *i* [#/h] from Equations (114) or (115) depending upon the dilution method.

Where the adjustment factors have been determined for each mode, they should be applied to each mode during the calculation of the weighted emission result in Equation (118) above.

9 Required results documentation

There are three spreadsheets associated with this Testing Protocol that should be used to document and record relevant aspects of the emissions testing:

- Spreadsheet 1 – Engine Settings, Drive Cycles and Test Results: Provides mode test point and weighting values for all rolling stock types (and engine and drive train combinations) that are in scope for the Testing Protocol. Mass-based emissions values for each mode test point for each pollutant in scope can be recorded, in the same order and structure as used to list the mode test points. See Section 11 for further details.
- Spreadsheet 2 – Emissions Calculations Template: Contains all the calculation steps and equations listed in Section 8 and allows use of any of the four balance methods described in Section 4. All relevant variables can be entered to derive final mass-based emissions values.
- Spreadsheet 3 – Additional Data Requirements: Enables documentation of key configurations and components for selected mitigation options (such as PM abatement, SCR and battery hybrid) where these characteristics can affect emissions reduction performance. See Section 10 for further details.

10 Additional data requirements for specific mitigation options

For certain mitigation options the exact configuration or characteristics of multiple components can have a significant impact on the effectiveness of the mitigation option on reducing emissions. Consequently, it will be important to first record these characteristics and configurations for the mitigation option when it was tested and then again when the solution is supplied and delivered for use in operational service. This will ensure that “what is supplied is what was tested”.

Spreadsheet 3 (Additional Data Requirements) provides a list of key characteristics that should be recorded when testing an emissions mitigation solution as well as when that solution is then installed in service. Detailed lists of the relevant data items are provided for:

- PM reduction in exhaust
- NOx reduction in exhaust
- retrofitted systems using battery technologies.

10.1 Critical component changes

Changing certain engine or mitigation solution components may have detrimental effect on the emissions performance of the rolling stock. Consequently, additional testing may be required. A representative list of such components, either general or specific to particular solutions, is provided in associated Spreadsheet 3.

11 Mode test points and total weightings by rolling stock type

The derivation of mode test points and time-based drive cycle weightings appropriate to different rolling stock types in their current state is described in the associated Methodology Report. These are designed to be typical averages but will vary for many reasons, for example, for passenger services due to:

- maximum line speeds being substantially slower the maximum rolling stock design speed
- driving style
- stopping patterns (density of stops)
- gradients (flatter routes versus hilly routes)
- diagramming efficiency of routes (how much time spend stationary between services).

Hence in some situations it may be best to use route or service group-specific weightings instead. These can be derived from on-train monitoring recorder (OTMR) or remote condition monitoring (RCM) data and infilled with learnings from audio recording. 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 13. 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 the Notch 7 test mode points are over 90% in the example in Table 14. This example 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 will have more columns for higher rpm.

Table 13 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 14 Example weightings for DHMU/DMMU 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%

Specific values for each locomotive or train class (and tailored for each relevant engine and drive train combination variant) that is in scope are provided on separate tabs in associated Spreadsheet 1 (Engine Mode Test Points) for the following cases:

- Class 150/153/155/156, Cummins NTA855 R5 (285 bhp)
- Class 158/159, Cummins NTA855 R1 (350 bhp)
- Class 158/159, Cummins NTA855 R3 (400 bhp)
- Class 158/159, Perkins TWH2006 (350 bhp)
- Class 165 (75 mph max speed)
- Class 165/166 (90 mph max speed)
- Class 168/170/171
- Class 172
- Class 175
- Class 180
- Class 185
- Class 220/221/222
- Class 66
- Class 68, no ETS load (i.e. freight use)
- Class 68, with max ETS load (i.e. passenger use)
- Class 70.

11.1 Weightings for station and onboard scenarios

Alternative weightings for certain specific situations can be developed to assess specific exposure and potential reductions with certain measures under those circumstances.

Drive cycles developed to assess onboard exposure weightings would have lower idle mode test point weightings and comparatively higher weights for all the Notch 1-7 mode test points.

Station focused testing would be even more dominated by idle than the total rolling stock usage weightings. In many cases station weightings could be simplified to a combination of idle (both while coasting or braking on approach and while stationary) and Notch 4 or 5 (depending on rolling stock and driver training at the operator) at high engine rpm for the initial acceleration out of the station up to circa 15 mph. The dwell times at stations will also vary and be substantially longer at termini. At termini engine shut down may also be used and the emissions associated with restarting an engine also need to be included. For rolling stock fitted with SCR, the post-SCR NOx emissions at Idle will vary over the first 10 minutes after the transition to Idle (e.g. from the start of coasting). This will often lead to the need to model potential station weightings and emissions on a specific rolling stock and station basis as the individual station and service parameters will vary considerably, substantially affecting the outcomes.

12 References

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ISO 8178-1, Reciprocating internal combustion engines — Exhaust emission measurement — Part 1: Test-bed measurement systems of gaseous and particulate emissions.

ISO 8178-2, Reciprocating internal combustion engines — Exhaust emission measurement — Part 2: Measurement of gaseous and particulate exhaust emissions under field conditions.

ISO 8178-4, Reciprocating internal combustion engines — Exhaust emission measurement — Part 4: Steady-state and transient test cycles for different engine applications.

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US EPA (2009). Emission Factors for Locomotives. EPA-420-F-09-025.

13 Bibliography

This section lists emission standards, testing requirement and other relevant documentation grouped by publishing organisation and then by document number.

California Air Resources Board (CARB)

CARB, Rulemaking on Amendments to Off-Road Compression-Ignition Engine Regulation and later emission standards, compliance requirements and test procedures, 2000

United Nations Economic Commission for Europe (UNECE)

UN ECE R24, Uniform provisions concerning; I: The approval of compression ignition (C.I.) engines with regard to the emission of visible pollutants; II: The approval of motor vehicles with regard to the installation of C.I. engines of an approved type; III: The approval of motor vehicles equipped with C.I. engines with regard to the emission of visible pollutants by the engine; IV: The measurement of power of C.I. engine

UN ECE R49, Uniform provisions concerning the measures to be taken against the emission of gaseous and particulate pollutants from compression-ignition engines and positive ignition engines for use in vehicles

UN ECE R 96, Uniform provisions concerning the approval of compression ignition (C.I.) engines to be installed in agricultural and forestry tractors and in non-road mobile machinery with regard to the emissions of pollutants by the engine

UN ECE R 120, Uniform provisions concerning the approval of internal combustion engines to be installed in agricultural and forestry tractors and in non-road mobile machinery, with regard to the measurement of the net power, net torque and specific fuel consumption

UN ECE Global technical regulation No. 11 – Engine Emissions from agricultural and forestry tractors and from non-road mobile machinery

European Committee for Standardisation (CEN)

EN 1822:2008, High efficiency air filters (EPA, HEPA and ULPA)

European Union (EU)

88/77/EEC:1988, Council directive in the approximation of the laws of the member states relating to the measures to be taken against the emission of gaseous pollutants from diesel engines for use in vehicles

97/68/EC: 1998, Directive 97/68/EC of the European Parliament and of the Council of 16 December 1997 on the approximation of the laws of the Member States relating to measures against the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery

International Standards Organisation (ISO)

ISO 1585, Road vehicles — Engine test code — Net power

ISO 2534, Road vehicles — Engine test code — Gross power

ISO 2710-1, Reciprocating internal combustion engines — Vocabulary — Part 1: Terms for engine design and operation

ISO 2710-2, Reciprocating internal combustion engines — Vocabulary — Part 2: Terms for engine maintenance

ISO 3046-1, Reciprocating internal combustion engines — Performance — Part 1: Declarations of power, fuel and lubricating oil consumptions, and test methods — Additional requirements for engines for general use

ISO 3046-3, Reciprocating internal combustion engines — Performance — Part 3: Test measurements

ISO/TR 3313, Measurement of fluid flow in closed conduits — Guidelines on the effects of flow pulsations on flow-measurement instruments

ISO 5167-1, Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full — Part 1: General principles and requirements

ISO 5167-2, Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full — Part 2: Orifice plates

ISO 5167-3, Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full — Part 3: Nozzles and Venturi nozzles

ISO 5167-4, Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full — Part 4: Venturi tubes

ISO 5168, Measurement of fluid flow — Procedures for the evaluation of uncertainties

ISO 5725-1, Accuracy (trueness and precision) of measurement methods and results — Part 1: General principles and definitions

ISO 5725-2, Accuracy (trueness and precision) of measurement methods and results — Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method

ISO 5725-3, Accuracy (trueness and precision) of measurement methods and results — Part 3: Intermediate measures of the precision of a standard measurement method

ISO 5725-4, Accuracy (trueness and precision) of measurement methods and results — Part 4: Basic methods for the determination of the trueness of a standard measurement method

ISO 5725-6, Accuracy (trueness and precision) of measurement methods and results — Part 6: Use in practice of accuracy values

ISO/TR 7066-1, Assessment of uncertainty in calibration and use of flow measurement devices — Part 1: Linear calibration relationships

ISO 7066-2, Assessment of uncertainty in the calibration and use of flow measurement devices — Part 2: Non-linear calibration relationships

ISO 8178-1, Reciprocating internal combustion engines — Exhaust emission measurement — Part 1: Test-bed measurement systems of gaseous and particulate emissions

ISO 8178-2, Reciprocating internal combustion engines — Exhaust emission measurement — Part 2: Measurement of gaseous and particulate exhaust emissions under field conditions

ISO 8178-3, Reciprocating internal combustion engines — Exhaust emission measurement — Part 3: Test procedures for measurement of exhaust gas smoke emissions from compression ignition engines using a filter type smoke meter

ISO 8178-4, Reciprocating internal combustion engines — Exhaust emission measurement — Part 4: Steady-state and transient test cycles for different engine applications

ISO 8178-5, Reciprocating internal combustion engines — Exhaust emission measurement — Part 5: Test fuels

ISO 8178-6, Reciprocating internal combustion engines — Exhaust emission measurement — Part 6: Report of measuring results and test

ISO 8178-9, Reciprocating internal combustion engines — Exhaust emission measurement — Part 9: Test cycles and test procedures for test bed measurement of exhaust gas smoke emissions from compression ignition engines operating under transient conditions

ISO 8178-10, Reciprocating internal combustion engines — Exhaust emission measurement — Part 10: Test cycles and test procedures for field measurement of exhaust gas smoke emissions from compression ignition engines operating under transient conditions

ISO 8528-1, Reciprocating internal combustion engine driven alternating current generating sets — Part 1: Application, ratings and performance

ISO 9096, Stationary source emissions — Manual determination of mass concentration of particulate matter

ISO 10054, Internal combustion compression-ignition engines — Measurement apparatus for smoke from engines operating under steady-state conditions — Filter-type smokemeter

ISO 14396, Reciprocating internal combustion engines — Determination and method for the measurement of engine power — Additional requirements for exhaust emission tests in accordance with ISO 8178

ISO 15550, Internal combustion engines — Determination and method for the measurement of engine power — General requirements

ISO 16183, Heavy duty engines — Measurement of gaseous emissions from raw exhaust gas and of particulate emissions using partial flow dilution systems under transient test conditions

SAE International (formerly the Society of Automotive Engineers)

SAE J177, Measurement of Carbon Dioxide, Carbon Monoxide and Oxides of Nitrogen in Diesel Exhaust

SAE J244, Measurement of intake air or exhaust gas flow of diesel engines

SAE J1003, Diesel Engine Emission Measurement Procedure

SAE J1088, Test Procedure for the Measurement of Gaseous Exhaust Emissions from Small Utility Engines

SAE J1151, Methane measurement using gas chromatography

SAE J1936, Chemical Methods for the Measurement of Non-regulated Diesel Emissions

SAE J2992, FTIR Gas Analyzer Performance Evaluation / Qualification for Automotive Testing

SAE Technical Paper 770141, Optimization of a Flame Ionization Detector for Determination of Hydrocarbon in Diluted Automotive Exhausts

US Environmental Protection Agency (EPA) rules published in the Code of Federal Regulations (CFR)

US Federal Register, 40 CFR Part 60 — Standards of Performance for New Stationary Sources

US Federal Register, 40 CFR Part 85 — Control of air pollution from mobile sources

US Federal Register, 40 CFR Part 86 — Control of emissions from new and in-use highway vehicles and engines

US Federal Register, 40 CFR Part 89 — Control of emissions from new and in-use nonroad compression-ignition engines

US Federal Register, 40 CFR Part 92 — Control of air pollution from locomotives and locomotive engines

US Federal Register, 40 CFR Part 1033 — Control of emissions from locomotives

US Federal Register, 40 CFR Part 1039 — Control of emissions from new and in-use nonroad compression-ignition engines

US Federal Register, 40 CFR Part 1065 — General compliance provisions for highway, stationary, and nonroad programs

US Federal Register, 40 CFR Part 1068 — Engine-testing procedures

14 Relevant definitions, terms and constants

Table 15 Symbols and abbreviated terms for fuel composition

Symbol	Definition
w_H	Hydrogen content of fuel, % mass
w_C	Carbon content of fuel, % mass
w_S	Sulphur content of fuel, % mass
w_N	Nitrogen content of fuel, % mass
w_O	Oxygen content of fuel, % mass
α	Molar hydrogen-to-carbon ratio (H/C)
β	Molar carbon-to-carbon ratio (C/C)
γ	Molar sulphur-to-carbon ratio (S/C)
δ	Molar nitrogen-to-carbon ratio (N/C)
ε	Molar oxygen-to-carbon ratio (O/C)
Example referring to a fuel: CβHαOεNδSγ	

Table 16 Symbols and abbreviated terms for chemical components

Symbol	Chemical component
Ar	Argon
C1	Carbon 1 equivalent hydrocarbon
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
H	Atomic hydrogen
H_2	Molecular hydrogen
H_2O	Water
He	Helium
N_2	Molecular nitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
NO	Nitric oxide
NO_2	Nitrogen dioxide
O_2	Oxygen
S	Sulphur
SO_2	Sulphur dioxide

Table 17 Key constants

Symbol	Description	Value	Unit
A_{rH}	Relative atomic mass of hydrogen	1.0079	g/mol
A_{rC}	Relative atomic mass of carbon	12.011	g/mol
A_{rS}	Relative atomic mass of sulphur	32.065	g/mol
A_{rN}	Relative atomic mass of nitrogen	14.007	g/mol
A_{rO}	Relative atomic mass of oxygen	15.999	g/mol
M_{rAr}	Relative atomic mass of argon	39.900	g/mol
M_{rH2O}	Molar mass of water	18.015	g/mol
M_{rCO2}	Molar mass of carbon dioxide	44.010	g/mol
M_{rCO}	Molar mass of carbon monoxide	28.011	g/mol
M_{rO2}	Molar mass of oxygen	31.999	g/mol
M_{rN2}	Molar mass of nitrogen	28.011	g/mol
M_{rNO}	Molar mass of nitric oxide	30.008	g/mol
M_{rNO2}	Molar mass of nitrogen dioxide	46.010	g/mol
M_{rSO2}	Molar mass of sulphur dioxide	64.066	g/mol
$M_{r\text{-}ig}$	Molar mass of inert gases	28.145	g/mol
V_{mH2O}	Molar volume of water	22,401	l/mol
V_{mCO2}	Molar volume of carbon dioxide	22,262	l/mol
V_{mCO}	Molar volume of carbon monoxide	22,408	l/mol
V_{mO2}	Molar volume of oxygen	22,392	l/mol
V_{mN2}	Molar volume of nitrogen	22,390	l/mol
V_{mNO}	Molar volume of nitric oxide	22,391	l/mol
V_{mNO2}	Molar volume of nitrogen dioxide	21,809	l/mol
V_{mSO2}	Molar volume of sulphur dioxide	21,891	l/mol
$V_{r\text{-}ig}$	Molar volume of inert gases	22,390	g/mol

Table 18 Key variables and notation

Symbol	Definition	Unit
A_r	Relative atomic mass	g/mol
A/F_{st}	Stoichiometric air to fuel ratio	—
c_b	Background concentration of tracer gas in intake air	µmol/mol
c_d	Concentration in the dilution air	% (V/V)
c_{CO2D}	Dry Concentration of CO_2	%
c_{COD}	Dry Concentration of CO	µmol/mol

Symbol	Definition	Unit
c_{HCW}	Wet Concentration of HC	µmol/mol
$c_{mix,i}$	Instantaneous concentration of tracer gas after mixing	µmol/mol
c_{NOD}	Dry Concentration of NO	µmol/mol
c_{NO2D}	Dry Concentration of NO_2	µmol/mol
c_{NOxD}	Dry Concentration of NO_x	µmol/mol
c_{O2D}	Dry Concentration of O_2	%
c_s	Average corrected concentration of particles from the diluted exhaust gas corrected at standard conditions	$\#/cm^3$
D	Dilution factor	—
d	Diameter	m
E	Conversion efficiency	%
e_{gas}	Specific emission of gaseous components	g/kWh
e_{PM}	Specific emission of particulates	g/kWh
e_{PN}	Number of particles emitted	#/kWh
e_w	Weighted specific emission	g/kWh
F_S	stoichiometric factor	—
f	Data sampling rate	Hz
f_a	Laboratory atmospheric factor	—
f_c	Carbon factor	—
f_{fd}	Fuel specific factor for exhaust flow calculation on dry basis	—
f_{fh}	Fuel specific factor used for the calculations of wet concentrations from dry concentrations	—
f_{fw}	Fuel specific factor for exhaust flow calculation on wet basis	—
f_{PF}	Penetration fraction	%
f_r	Mean particle concentration reduction factor of the volatile particle remover specific to the dilution settings used for the test	—
f_{RF}	Response factor	—
f_{WF}	Weighting factor	—

Symbol	Definition	Unit
f_{WFei}	Effective weighting factor for a mode, for the single-filter PM method	—
H_a	Absolute humidity of the intake air (g water/kg dry air)	g/kg
H_d	Absolute humidity of the dilution air (g water/kg dry air)	g/kg
i	Subscript denoting an individual mode	—
i	Subscript denoting an instantaneous measurement (e.g. - Hz)	—
k_f	Fuel specific factor	—
$k_{h,D}$	Humidity correction factor for NO_x for CI engines	—
k_w	Dry to wet correction factor for the raw exhaust gas	—
$k_{w,d}$	Dry to wet correction factor for the dilution air	—
$k_{w,e}$	Dry to wet correction factor for the diluted exhaust gas	—
$k_{w,r}$	Dry to wet correction factor for the raw exhaust gas	—
L	% torque	—
λ	Instantaneous excess air ratio	—
M	Molar mass	g/mol
M_{gas}	Molar mass of gaseous components	g/mol
M_r	Molar mass	g/mol
m	Mass	kg
m_b	Mass of collected background particulates of dilution air	mg
m_d	Mass of the dilution air sample passed through the particulate sampling filters	kg
m_{ed}	Mass of diluted exhaust gas over the cycle	kg
m_{edf}	Mass of equivalent diluted exhaust gas over the cycle	kg
m_{ew}	Mass of raw exhaust over the test mode	kg
m_f	Particulate sample mass collected	mg
$m_{f,d}$	Particulate sample mass of the dilution air collected	mg
m_{gas}	Mass of gaseous emissions over the test cycle	g
m_{PM}	Mass of particulate emissions over the test cycle	g
m_{se}	Exhaust sample mass over the cycle	kg

Symbol	Definition	Unit
m_{sed}	Mass of diluted exhaust gas passing the dilution tunnel	kg
m_{sep}	Mass of the diluted exhaust sample passed through the particulate sampling filters	kg
m_{set}	Mass of double diluted exhaust gas through particulate filter	kg
m_{ssd}	mass of secondary dilution air	kg
μ	Dynamic viscosity of exhaust gas	Pa*s
N	Number of particles	#
$\dot{N}$	Rate of emission of particles during the individual discrete mode	#/h
n	Engine speed	min^{-1}
n_{hi}	High engine speed	min^{-1}
n_{lo}	Low engine speed	min^{-1}
P	Power	kW
P_{aux}	Declared total power absorbed by auxiliaries fitted for the test and not required by ISO −4396	kW
P_{max}	Maximum observed or declared power at the test speed under the test conditions (specified by the manufacturer)	kW
p	Pressure	kPa
p_a	Saturation vapour pressure of the intake air	kPa
p_b	Total barometric pressure	kPa
p_d	Saturation vapour pressure of the dilution air	kPa
p_r	Water vapor pressure after cooling bath	kPa
p_s	Dry atmospheric pressure	kPa
q_{mad}	Dry intake air flow rate	kg/s
q_{maw}	Intake air mass flow rate on wet basis	kg/s
q_{mdew}	Diluted exhaust gas mass flow rate on wet basis	kg/s
q_{mdw}	Dilution air mass flow rate on wet basis	kg/s
q_{medf}	Equivalent diluted exhaust gas mass flow rate on wet basis	kg/s
q_{mew}	Exhaust gas mass flow rate on wet basis	kg/s
q_{mf}	Fuel mass flow rate	kg/s

Symbol	Definition	Unit
q_{mgas}	Emission mass flow rate of individual gas	g/h
q_{mp}	Sample flow of exhaust gas into partial flow dilution system	kg/s
q_{sw}	mass flow rate fed back into dilution tunnel to compensate for particle number sample extraction	kg/s
q_V	Volume flow rate	m^3/s
q_v	Volume flow	m^3/h
q_{vew}	Volumetric flow rate of raw exhaust gas	m^3/s
q_{vaw}	Volume flow of wet intake air	m^3/h
q_{ved}	Volume flow of dry exhaust	m^3/h
q_{vad}	Volume flow of dry intake air	m^3/h
q_{vt}	Tracer gas flow rate	cm^3/min
R	Molar gas constant	J/(mol K)
r_d	Dilution ratio	—
r_s	Average sample ratio	—
ρ	Density	kg/m^3
ρ_e	Average wet basis density of the exhaust gas at standard conditions (wet basis is default if not stated)	kg/m^3
$\rho_{e,i}$	Instantaneous density of the exhaust gas at standard conditions	kg/m^3
ρ_{ed}	Average dry basis density of the exhaust gas at standard conditions	kg/m^3
ρ_{ew}	Average wet basis density of the exhaust gas at standard conditions	kg/m^3
S	Dynamometer setting	kW
T	Temperature	°C
T	Engine torque	Nm
T_a	Absolute temperature of the intake air	K
T_{dew}	Absolute dewpoint temperature	K
T_{ref}	Absolute reference temperature (of combustion air: 298 K)	K
t	Time	s
$\emptyset_a$	Atmospheric relative humidity	%

Symbol	Definition	Unit
u_{gas}	Ratio between densities of gas component and exhaust gas	—
V	Volume	m^3
V_m	Molar volume	l/mol
W	Work	kWh
W_{act}	Actual cycle work of the respective test cycle	kWh
w_{ox}	Oxygen content of dry intake air	% mass
w_{inert}	Inert gas content of dry intake air	% mass
x	Concentration	µmol/mol or %
$\bar{y}$	Arithmetic mean	—