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Reciprocating internal combustion engines — Exhaust emission measurement —

Part 4: Steady-state and transient test cycles for different engine applications

Moteurs alternatifs à combustion interne — Mesurage des émissions de gaz d'échappement —

Partie 4: Cycles d'essai à l'état stable et transitoires pour différentes applications des moteurs

Reference number
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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

The committee responsible for this document is ISO/TC 70, *Reciprocating internal combustion engines*, Subcommittee SC 8, *Exhaust gas emission measurement*.

This fourth edition cancels and replaces the third edition (ISO 8178-4:2017), which has been technically revised.

The main changes compared to the previous edition are as follows:

— amendment of the information regarding the determination of the background concentration;

— revision of particle number emission evaluation;

— addition of electrical equipment in the auxiliary table;

A list of all the parts in the ISO 8178 series, can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

In comparison with engines for on-road applications, engines for non-road use are made in a much wider range of power output and configuration and are used in a great number of different applications.

The objective of this document is to rationalize the test procedures for non-road engines in order to simplify and make more cost effective the drafting of legislation, the development of engine specifications and the certification of engines to control gaseous and particulate emissions.

This document embraces three concepts in order to achieve the objectives.

The first principle is to group applications with similar engine operating characteristics in order to reduce the number of test cycles to a minimum, but ensure that the test cycles are representative of actual engine operation.

The second principle is to express the emissions results on the basis of brake power as defined in ISO 8178-1. This ensures that alternative engine applications do not result in a multiplicity of tests.

The third principle is the incorporation of an engine family concept in which engines with similar emission characteristics and of similar design may be represented by the highest emitting engine within the group.

Reciprocating internal combustion engines — Exhaust emission measurement —

Part 4:
Steady-state and transient test cycles for different engine applications

1 Scope

This document specifies the test cycles, the test procedures and the evaluation of gaseous and particulate exhaust emissions from reciprocating internal combustion (RIC) engines coupled to a dynamometer. With certain restrictions, this document can also be used for measurements at site. The tests are carried out under steady-state and transient operation using test cycles which are representative of given applications.

This document is applicable to RIC engines for mobile, transportable and stationary use, excluding engines for on-road transport of passengers and goods. It can be applied to engines for non-road use, e.g. for earth-moving machines, generating sets and for other applications. For engines used in machinery covered by additional requirements (e.g. occupational health and safety regulations, regulations for power plants), additional test conditions and special evaluation methods can apply.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 8178-1:2020, *Reciprocating internal combustion engines — Exhaust emission measurement — Part 1: Test-bed measurement of gaseous and particulate exhaust emissions*

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

ASTM E29–06b, *Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
adjustment factors
additive (upward adjustment factor and downward adjustment factor) or multiplicative factors to be used for engines equipped with emission controls, that are regenerated on an infrequent (periodic) basis

3.2
applicable emission limit
emission limit to which an engine is subject

3.3
aqueous condensation
precipitation of water-containing constituents from a gas phase to a liquid phase

Note 1 to entry: Aqueous condensation is a function of humidity, pressure, temperature, and concentrations of other constituents such as sulphuric acid. These parameters vary as a function of engine intake-air humidity, dilution-air humidity, engine air-to-fuel ratio, and fuel composition — including the amount of hydrogen and sulphur in the fuel.

3.4
atmospheric pressure
wet, absolute, atmospheric static pressure

Note 1 to entry: If the atmospheric pressure is measured in a duct, negligible pressure losses shall be ensured between the atmosphere and the measurement location, and changes in the duct's static pressure resulting from the flow shall be accounted for.

3.5
calibration
process of setting a measurement system's response so that its output agrees with a range of reference signals

Note 1 to entry: Contrast with *verification* (3.78).

3.6
calibration gas
purified gas mixture used to calibrate gas analysers meeting the specifications of ISO 8178-1:2020, 9.2

Note 1 to entry: Calibration gases and *span gases* (3.65) are qualitatively the same, but differ in terms of their primary function. Various performance *verification* (3.78) checks for gas analysers and sample handling components might refer to either calibration gases or span gases.

3.7
certification
process of obtaining a certificate of conformity

3.8
compression ignition engine
CI engine
engine that works on the compression-ignition principle

3.9
constant-speed engine
engine whose *type approval* (3.76) or *certification* (3.7) is limited to *constant-speed operation* (3.10)

Note 1 to entry: Engines whose constant-speed *governor* (3.29) function is removed or disabled are no longer constant-speed engines.

3.10
constant-speed operation
engine operation with a *governor* (3.29) that automatically controls the *operator demand* (3.47) to maintain engine speed, even under changing load

Note 1 to entry: Governors do not always maintain speed exactly constant. Typically, speed can decrease 0,1 % to 10 % below the speed at zero load, such that the minimum speed occurs near the engine's point of *maximum power* (3.39).

3.11
continuous regeneration
regeneration (3.59) process of an *exhaust after-treatment system* (3.22) that occurs either in a sustained manner or at least once over the applicable *transient test cycle* (3.75) or ramped-modal cycle; in contrast to *infrequent (periodic) regeneration* (3.33)

3.12
conversion efficiency of non-methane cutter
conversion efficiency of NMC
E
efficiency of the conversion of an NMC that is used for the removal of the *non-methane hydrocarbons* (3.44) from the sample gas by oxidizing all *hydrocarbons* (3.30) except methane

Note 1 to entry: Ideally, the conversion for methane is 0 % (E_{CH4} = 0) and for the other hydrocarbons represented by ethane 100 % (E_{C2H6} = 100 %). For the accurate measurement of *NMHC* (3.44), the two efficiencies shall be determined and used for the calculation of the NMHC emission mass flow rate for methane and ethane. Contrast with *penetration fraction* (3.52).

3.13
delay time
difference in time between the change of the component to be measured at the reference point and a system response of 10 % of the final reading (t_{10}) with the sampling *probe* (3.54) being defined as the reference point

Note 1 to entry: For the gaseous components, this is the transport time of the measured component from the sampling probe to the detector (see Figure 1).

3.14
deNO$_x$ system
exhaust after-treatment system (3.22) designed to reduce emissions of *oxides of nitrogen (NOx)* (3.48)

EXAMPLE Passive and active lean NO_x catalysts, NO_x adsorbers and selective catalytic reduction (SCR) systems.

3.15
dew point
measure of humidity stated as the equilibrium temperature at which water condenses under a given pressure from moist air with a given absolute humidity

Note 1 to entry: Dew point is specified as a temperature in °C or K, and is valid only for the pressure at which it is measured.

3.16
drift
difference between a zero or *calibration* (3.5) signal and the respective value reported by a measurement instrument immediately after it was used in an emission test, as long as the instrument was *zeroed* (3.79) and *spanned* (3.64) just before the test

3.17
dual-fuel engine
engine system that is designed to simultaneously operate with *liquid fuel* (3.36) and a *gaseous fuel* (3.26), both fuels being metered separately, where the consumed amount of one of the fuels relative to the other one may vary depending on the operation

3.18
emission-control system
device, system, or element of design that controls or reduces the emissions of regulated pollutants from an engine

3.19
engine family
manufacturers grouping of engines which, through their design as defined in ISO 8178-7, have similar exhaust emission characteristics

Note 1 to entry: All members of the family shall comply with the *applicable emission limit* (3.2) values.

3.20
engine governed speed
engine operating speed when it is controlled by the installed *governor* (3.29)

3.21
engine type
category of engines which do not differ in essential engine characteristics

3.22
exhaust after-treatment system
catalyst, particulate filter, *deNOx system* (3.14), combined deNO$_x$ particulate filter or any other emission-reducing device that is installed downstream of the engine

Note 1 to entry: This definition excludes *exhaust-gas recirculation (EGR)* (3.23) and turbochargers, which are considered an integral part of the engine.

3.23
exhaust-gas recirculation
EGR
technology that reduces emissions by routing exhaust gases that had been exhausted from the combustion chamber(s) back into the engine to be mixed with incoming air before or during combustion

Note 1 to entry: The use of valve timing to increase the amount of residual exhaust gas in the combustion chamber(s) that is mixed with incoming air before or during combustion is not considered exhaust-gas recirculation for the purposes of this document.

3.24
full flow dilution
method of mixing the exhaust gas flow with dilution air prior to separating a fraction of the diluted exhaust gas flow for analysis

3.25
gas energy ratio
GER
value of the energy content (for a *dual-fuel engine* (3.17)) of the *gaseous fuel* (3.26) divided by the energy content of both fuels (liquid and gaseous), the energy content of the fuels being defined as the lower heating value

3.26
gaseous fuel
fuel which is wholly gaseous at standard ambient conditions

Note 1 to entry: Ambient temperature 298 K (25 °C), absolute ambient pressure 101,3 kPa.

3.27
gaseous pollutants
exhaust gas emissions of carbon monoxide, *NOx* (3.48), expressed in NO_2 equivalent, *hydrocarbons* (3.30)

Note 1 to entry: They are total hydrocarbons, *non-methane hydrocarbons* (3.44) and methane.

3.28
good engineering judgement
judgement made consistent with generally accepted scientific and engineering principles and available relevant information

3.29
governor
device or control strategy that automatically controls engine speed or load that is not an over-speed limiter

3.30
hydrocarbon
HC
hydrocarbon group on which the emission standards are based for each type of fuel and engine

EXAMPLE *THC* (3.73), *NMHC* (3.44) as applicable

3.31
high speed
n_{hi}
highest engine speed where 70 % of the *maximum power* (3.39) occurs

3.32
idle speed
engine speed declared by the manufacturer that conforms to the requirements of 7.2.4

3.33
infrequent regeneration
periodic regeneration
regeneration (3.59) process of an *exhaust after-treatment system* (3.22) that occurs periodically in typically less than 100 hours of normal engine operation

Note 1 to entry: During cycles where regeneration occurs, emission standards may be exceeded.

3.34
intermediate speed
engine speed declared by the manufacturer that conforms to the requirements of 7.2.3

3.35
linearity
degree to which measured values agree with respective reference values quantified using a linear regression of pairs of measured values and reference values over a range of values expected or observed during testing

3.36
liquid fuel
fuel which exists in the liquid state under standard ambient conditions (298 K, absolute ambient pressure 101,3 kPa)

3.37
low speed
n_{lo}
lowest engine speed where 50 % of the *maximum power* (3.39) occurs

3.38
maximum no load speed
engine speed at which an engine *governor* (3.29) function controls engine speed with *operator demand* (3.47) at maximum and with zero load applied

3.39
maximum power
maximum power as designed by the manufacturer

Note 1 to entry: It is expressed in kW.

3.40
maximum test speed
engine speed determined from the curve of engine speed versus power according to 7.2.1

3.41
maximum torque speed
engine speed at which the maximum torque is obtained from the engine, as designed by the manufacturer

3.42
mode
engine operating point characterized by a speed and a torque (or a power output)

3.43
mode length
time between leaving the speed and/or torque of the previous *mode* (3.42) or the preconditioning phase and the beginning of the following mode

Note 1 to entry: It includes the time during which speed and/or torque is being changed and the stabilization at the beginning of each mode.

3.44
non-methane hydrocarbons
NMHC
sum of all *hydrocarbon* (3.30) species except methane

3.45
normalized speed and torque
speed and torque values expressed as a percentage of a maximum value

3.46
open crankcase emissions
flow from an engine's crankcase that is emitted directly into the environment

Note 1 to entry: Crankcase emissions are not "open crankcase emissions" if the engine is designed to always route all crankcase emissions back into the engine (for example, through the intake system or an aftertreatment system) such that all the crankcase emissions, or their products, are emitted into the environment only through the engine exhaust system.

3.47
operator demand
engine operator's input to control engine output

Note 1 to entry: The "operator" may be a person (i.e. manual), or a *governor* (3.29) (i.e. automatic) that mechanically or electronically signals an input that demands engine output. Input may be from an accelerator pedal or signal, a throttle-control lever or signal, a fuel lever or signal, a speed lever or signal, or a governor setpoint or signal. Output means engine power, P, which is the product of engine speed, n, and engine torque, T.

3.48
oxides of nitrogen
NO_x
compounds containing only nitrogen and oxygen as measured by the *procedures* (3.55) specified in this document

Note 1 to entry: Oxides of nitrogen are expressed quantitatively as if the NO is in the form of NO_2, such that an effective molar mass is used for all oxides of nitrogen equivalent to that of NO_2.

3.49
partial pressure
pressure, *p*, attributable to a single gas in a gas mixture

Note 1 to entry: For an ideal gas, the partial pressure divided by the total pressure is equal to the constituent's molar concentration, *x*.

3.50
partial flow dilution
method of analysing the exhaust gas whereby a part of the total exhaust gas flow is separated, then mixed with an appropriate amount of dilution air prior to reaching the particulate sampling filter

3.51
particulate matter
PM
material collected on a specified filter medium after diluting exhaust with clean filtered air to a temperature and a point as specified in ISO 8178-1:2020, 8.1.4, primarily carbon, condensed *hydrocarbons* (3.30), and sulphates with associated water

3.52
penetration fraction
PF
deviation from ideal functioning of a non-methane cutter

Note 1 to entry: See *conversion efficiency of non-methane cutter (NMC)*, *E*, (3.12).

Note 2 to entry: An ideal non-methane cutter would have a methane penetration factor, $f_{PF\ CH4}$, of 1,000 (that is, a methane conversion efficiency E_{CH4} of 0), and the penetration fraction for all other *hydrocarbons* (3.30) would be 0,000, as represented by $f_{PF\ C2H6}$ (that is, an ethane conversion efficiency E_{C2H6} of 1). The relationship is: $f_{PF\ CH4} = 1 - E_{CH4}$ and $f_{PF\ C2H6} = 1 - E_{C2H6}$.

3.53
per cent load
fraction of the maximum available torque at an engine speed

3.54
probe
first section of the transfer line which transfers the sample to the next component in the sampling system

3.55
procedures
all aspects of engine testing, including the equipment specifications, *calibrations* (3.5), calculations and other protocols and specifications needed to measure emissions, unless otherwise specified

3.56
ramped-modal steady-state test cycle
test cycle (3.70) with a sequence of steady-state engine test *modes* (3.42) with defined speed and torque criteria at each mode and defined speed and torque ramps between these modes

3.57
rated power
value of the power, declared by the manufacturer, which an engine will deliver under the specified test conditions

Note 1 to entry: For details see ISO 14396.

3.58
rated speed
engine speed at which, according to the statement of the engine manufacturer, and conforming to the requirements of 7.2.2, the *rated power* (3.57) is delivered

Note 1 to entry: For details see ISO 14396.

3.59
regeneration
event during which emissions levels change while the after treatment performance is being restored by design

Note 1 to entry: Two types of regeneration can occur: *continuous regeneration* (3.11) (see 5.5.1.2.1) and *infrequent (periodic) regeneration* (3.33) (see 5.5.1.2.2).

3.60
response time
difference in time between the change of the component to be measured at the reference point and a system response of 90 % of the final reading (t_{90}) with the sampling *probe* (3.54) being defined as the reference point, whereby the change of the measured component is at least 60 % full scale (FS) and the devices for gas switching shall be specified to perform the gas switching in less than 0,1 s

Note 1 to entry: The system response time consists of the *delay time* (3.13) to the system and of the *rise time* (3.61) of the system.

3.61
rise time
difference in time of the 10 % and 90 % response of the final reading ($t_{90} - t_{10}$)

3.62
shared atmospheric pressure meter
atmospheric pressure (3.4) meter whose output is used as the atmospheric pressure for an entire test facility that has more than one dynamometer test cell

3.63
shared humidity measurement
humidity measurement that is used as the humidity for an entire test facility that has more than one dynamometer test cell

3.64
span, verb
adjust an instrument so that it gives a proper response to a *calibration* (3.5) standard that represents between 75 % and 100 % of the maximum value in the instrument range or expected range of use

3.65
span gas
purified gas mixture used to *span* (3.64) gas analysers meeting the specifications of ISO 8178-1:2020, 9.2

Note 1 to entry: *Calibration gases* (3.6) and span gases are qualitatively the same, but differ in terms of their primary function. Various performance *verification* (3.78) checks for gas analysers and sample handling components might refer to either calibration gases or span gases.

3.66
spark-ignition engine
SI engine
engine that works on the spark-ignition principle

3.67
specific emissions
mass emissions expressed in g/kWh; particulate Number (PN) emissions expressed in #/kWh

3.68
steady-state test
emission test in which engine speed and load are held at a finite set of nominally constant values

Note 1 to entry: Steady-state tests are either discrete-mode tests or ramped-modal tests.

3.69
stoichiometric
particular ratio of air and fuel such that if the fuel were fully oxidized, there would be no remaining fuel or oxygen

3.70
test cycle
duty cycle
sequence of test points each with a defined speed and torque to be followed by the engine under steady state or transient operating conditions

Note 1 to entry: Duty cycles are specified in Annexes A, B and C. A single duty cycle may consist of one or more test intervals (3.71).

3.71
test interval
duration of time over which brake-specific emissions are determined

Note 1 to entry: In cases where multiple test intervals occur over a *duty cycle* (3.70), the standard may specify additional calculations that weigh and combine results to arrive at composite values for comparison against the *applicable emission limits* (3.2).

3.72
tolerance
interval in which 95 % of a set of recorded values of a certain quantity shall lie, with the remaining 5 % of the recorded values deviating from the tolerance interval only due to measurement variability

Note 1 to entry: The specified recording frequencies and time intervals shall be used to determine if a quantity is within the applicable tolerance. For parameters not subject to measurement variability, tolerance means an absolute allowable range.

3.73
total hydrocarbon
THC
combined mass of organic compounds measured by the specified procedure for measuring total hydrocarbon

Note 1 to entry: Total hydrocarbon is expressed as a *hydrocarbon* (3.30) with a hydrogen-to-carbon mass ratio of 1,85:1 (Diesel), 1,93 (petrol (E10)), 2,525 (LPG), 4,0 (NG/biomethane) or 2,74 (ethanol (E85)).

3.74
transformation time
difference in time between the change of the component to be measured at the reference point and a system response of 50 % of the final reading (t_{50}) with the sampling *probe* (3.54) being defined as the reference point

Note 1 to entry: The transformation time is used for the signal alignment of different measurement instruments (see Figure 1).

3.75
transient test cycle
test cycle (3.70) with a sequence of *normalized speed and torque* (3.45) values that vary relatively quickly with time (NRTC)

3.76
type approval
approval of an *engine type* (3.21) with regard to its emissions measured in accordance with the *procedures* (3.55) specified in this document

3.77
variable-speed engine
engine that is not a *constant-speed engine* (3.9)

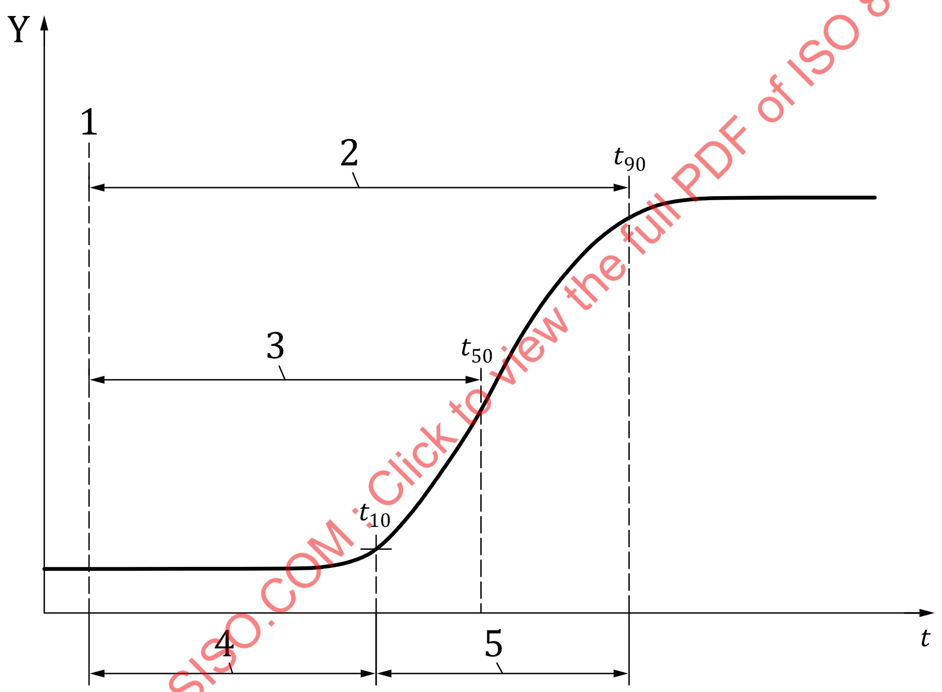
3.78
verification
evaluation of whether or not a measurement system's outputs agree with a range of applied reference signals to within one or more predetermined thresholds for acceptance

Note 1 to entry: Contrast with *calibration* (3.5).

3.79
zero, verb
adjust an instrument so it gives a zero response to a zero *calibration* (3.5) standard, such as purified nitrogen or purified air for measuring concentrations of emission constituents

3.80
zero gas
gas that yields a zero response in an analyser

Note 1 to entry: This may either be purified nitrogen, purified air, a combination of purified air and purified nitrogen.



Key

1 step input time
2 *response time* (3.60)
3 *transformation time* (3.74)
4 *delay time* (3.13)
5 *rise time* (3.61)
t time
Y response

Figure 1 — Definitions of system response: delay time, response time, rise time and transformation time

4 Symbols and abbreviated terms

4.1 General symbols

For the purposes of this document, the general symbols given in Table 1 apply.

Table 1 — General symbols

Symbol	Term	Unit
A	Relative atomic mass	g/mol
A/F_{st}	Stoichiometric air to fuel ratio	—
a_0	y intercept of the regression line	—
a_1	Slope of the regression line	—
C_d	CFV discharge coefficient [–]	—
c_d	Concentration in the dilution air	% (V/V)
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_{RF}	Response factor	—
f_{WF}	Weighting factor	—
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_{Dr}	Additive downward adjustment factor	—
k_f	Fuel specific factor	—
$k_{h,D}$	Humidity correction factor for NO_x for CI engines	—
$k_{h,G}$	Humidity correction factor for NO_x for SI engines	
k_{MDr}	Multiplicative downward adjustment factor	—
k_{MUr}	Multiplicative upward adjustment factor	—
k_r	Multiplicative regeneration factor	—
k_{Ur}	Additive upward adjustment factor	—
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	—

Table 1 *(continued)*

Symbol	Term	Unit
$k_{w,r}$	Dry to wet correction factor for the raw exhaust gas	—
L	%torque	—
λ	Excess air ratio	—
M	Molar mass	g/mol
M_{gas}	Molar mass of gaseous components	g/mol
m	Mass	kg
m_d	Mass of the dilution air sample passed through the particulate sampling filters	kg
m_{edf}	Mass of equivalent diluted exhaust gas over the cycle	kg
m_f	Particulate sample mass collected	mg
m_{ed}	mass of diluted exhaust gas over the cycle	kg
$m_{f,d}$	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
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
μ	Dynamic viscosity of exhaust gas	Pa*s
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 atmospheric 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
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_{Vt}	Tracer gas flow rate	cm^3/min

Table 1 *(continued)*

Symbol	Term	Unit
R	molar gas constant	J/(mol K)
r^2	Coefficient of determination	—
r_d	Dilution ratio	—
r_s	Average sample ratio	—
ρ	Density	kg/m3
S	Dynamometer setting	kW
S_{EE}	Standard error of estimate of y on x	—
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
t_{10}	Time between step input and 10 % of final reading	s
t_{50}	Time between step input and 50 % of final reading	s
t_{90}	Time between step input and 90 % of final reading	s
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
x	Concentration	µmol/mol or %
$\overline{y}$	Arithmetic mean	

4.2 Symbols and abbreviated terms for fuel composition

w_H hydrogen content of fuel, % mass

w_C carbon content of fuel, % mass

w_S sulfur 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: $C_\beta H_\alpha O_\varepsilon N_\delta S_\gamma$.

4.3 Symbols and abbreviated terms for chemical components

Ar	Argon
C_1	Carbon 1 equivalent hydrocarbon
C_2H_6	Ethane
C_2H_5OH	Ethanol
C_3H_8	Propane
CH_3OH	Methanol
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
H	Atomic hydrogen
H_2	Molecular hydrogen
H_2O	Water
HCHO	Formaldehyde
He	Helium
N_2	Molecular nitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
NO	Nitric oxide
NO_2	Nitrogen dioxide
O_2	Oxygen
RME	Rapeseed oil methylester
S	Sulphur
SO_2	Sulphur dioxide

4.4 Abbreviated terms

ASTM	American Society for Testing and Materials
CFV	Critical flow venturi
CI	Compression-ignition
CNG	Compressed natural gas
CVS	Constant volume sampling
deNOx	NO_x after-treatment system

EGR	Exhaust-gas recirculation
FID	Flame ionization detector
FS	Full scale
G_R, G_{23}, G_{25}	Gaseous EU reference fuels according to ISO 8178-5
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
NMC	Non-methane cutter
NRMM	Non-road mobile machinery
NRTC	Non road transient cycle
PDP	Positive displacement pump
PFS	Partial flow system
PTFE	Polytetrafluoroethylene (commonly known as Teflon®)[a]
RIC	Reciprocating internal combustion (engines)
RMC	Ramped-modal cycle
SAE	Society of Automotive Engineers
SSV	Subsonic venture

[a] Teflon® is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of this product.

5 Test conditions

5.1 Engine test conditions

5.1.1 Laboratory test conditions

The absolute temperature (T_a) of the engine air at the inlet to the engine expressed in Kelvin, and the dry atmospheric pressure (p_s), expressed in kPa shall be measured and the parameter f_a shall be determined according to the following provisions. In multi-cylinder engines having distinct groups of intake manifolds, such as in a "V" engine configuration, the average temperature of the distinct groups shall be taken. The parameter f_a shall be reported with the test results.

Naturally aspirated and mechanically supercharged engines:

$$f_a = \left[\frac{99}{p_s}\right] \times \left[\frac{T_a}{298}\right]^{0,7} \quad (1)$$

Turbocharged engines with or without cooling of the intake air:

$$f_a = \left[\frac{99}{p_s}\right]^{0,7} \times \left[\frac{T_a}{298}\right]^{1,5} \quad (2)$$

5.1.2 Test validity

a) For the test to be considered valid both the following conditions shall be met:

1) f_a shall be within the range $0,93 \le f_a \le 1,07$ except as permitted by b) and d);

2) the temperature of intake air shall be maintained to (25 ± 5) °C, as measured upstream of any engine component, except as permitted by c) and d).

b) Where the altitude of the laboratory in which the engine is being tested exceeds [600] m, with the agreement of the manufacturer f_a may exceed 1,07 on the condition that p_s shall not be less than 80 kPa.

c) Where the power of the engine being tested is greater than 560 kW, with the agreement of the manufacturer the maximum value of intake air temperature may exceed 30 °C on the condition that it shall not exceed 35 °C.

d) Where the altitude of the laboratory in which the engine is being tested exceeds [300] m and the power of the engine being tested is greater than 560 kW, with the agreement of the manufacturer f_a may exceed 1,07 on the condition that p_s shall not be less than 80 kPa and the maximum value of intake air temperature may exceed 30 °C on the condition that it shall not exceed 35 °C.

The following is allowed:

a) a shared atmospheric pressure meter as long as the equipment for handling intake air maintains ambient pressure, where the engine is tested, within ±1 kPa of the shared atmospheric pressure;

b) a shared humidity measurement for intake air as long as the equipment for handling intake air maintains dew point, where the engine is tested, within ±0,5 °C of the shared humidity measurement.

5.2 Engine power

The basis of specific emissions measurement is uncorrected brake power as defined in ISO 14396. The engine shall be submitted for testing with the auxiliaries needed for operating the engine.

5.2.1 Auxiliaries to be fitted

During the test, the auxiliaries necessary for the engine operation shall be installed on the test bench according to the requirements of Annex G.

Where the necessary auxiliaries cannot be fitted for the test, the power they absorb shall be determined and subtracted from the measured engine power.

5.2.2 Auxiliaries to be removed

Certain auxiliaries whose definition is linked with the operation of the machine and which may be mounted on the engine shall be removed for the test.

Where auxiliaries cannot be removed, the power they absorb in the unloaded condition may be determined and added to the measured engine power (see Table G.1, footnote h). If this value is greater than 3 % of the maximum power at the test speed it may be verified by the parties involved. The power absorbed by auxiliaries shall be used to adjust the set values and to calculate the work produced by the engine over the test cycle.

5.2.3 Determination of auxiliary power

The power absorbed by the auxiliaries/equipment needs only be determined, if:

a) auxiliaries/equipment required according to Annex G are not fitted to the engine; and/or

b) auxiliaries/equipment not required according to Annex G are fitted to the engine.

The values of auxiliary power and the measurement/calculation method for determining auxiliary power shall be submitted by the engine manufacturer for the whole operating area of the applicable test cycles, and approved by the parties involved.

5.2.4 Engine cycle work

The calculation of reference and actual cycle work (see 8.6.3.5) shall be based upon engine power according to 5.2. In this case, P_f and P_r of Formula (3) are zero, and P equals P_m.

If auxiliaries/equipment are installed according to 5.2.1 and/or 5.2.2, the power absorbed by them shall be used to correct each instantaneous cycle power value $P_{m,i}$, as follows:

$$P_i = P_{m,i} + P_{AUX} \tag{3}$$

where

$P_{m,i}$ is the measured engine power, kW;

P_{AUX} $= P_{r,i} - P_{f,i}$;

$P_{f,i}$ is the power absorbed by auxiliaries/equipment to be fitted for the test but that were not installed, kW;

$P_{r,i}$ is the power absorbed by auxiliaries/equipment to be removed for the test but that were installed, kW.

5.3 Engine intake air

5.3.1 General

The intake-air system installed on the engine or one that represents a typical in-use configuration shall be used. This includes the charge-air cooling and exhaust-gas recirculation systems.

5.3.2 Intake air restriction

An engine air intake system or a test laboratory system shall be used presenting an air intake restriction within ± 300 Pa of the maximum value specified by the manufacturer for a clean air cleaner at the rated speed and full load. Where this is not possible due to the design of the test laboratory air supply system a restriction not exceeding the value specified by the manufacturer for a dirty filter shall be permitted subject to prior approval of the parties involved. The static differential pressure of the restriction shall be measured at the location specified by the manufacturer. If the manufacturer does not specify a location, this pressure shall be measured upstream of any turbocharger or exhaust-gas recirculation system connection to the intake air system.

When the maximum test speed (MTS) defined in 3.40 is being used in place of rated speed to run the test cycle then this speed may be used in place of rated speed when setting the intake air restriction.

5.3.3 Engines with charge air cooling

A charge-air cooling system with a total intake-air capacity that represents the production engine's in-use installation shall be used. Any laboratory charge-air cooling system shall be designed to minimize accumulation of condensate. Any accumulated condensate shall be drained and all drains shall be completely closed before emission testing. The drains shall be kept closed during the emission test. Coolant conditions shall be maintained as follows:

a) A coolant temperature of at least 20 °C shall be maintained at the inlet to the charge-air cooler throughout testing.

b) At the rated speed and full load, the coolant flow rate shall be set to achieve an air temperature within ±5 °C of the value designed by the manufacturer after the charge-air cooler's outlet. The air-outlet temperature shall be measured at the location specified by the manufacturer. This coolant flow rate set point shall be used throughout testing.

c) If the engine manufacturer specifies pressure-drop limits across the charge-air cooling system, it shall be ensured that the pressure drop across the charge-air cooling system at engine conditions specified by the manufacturer is within the manufacturer's specified limit(s). The pressure drop shall be measured at the manufacturer's specified locations.

When the maximum test speed (MTS) defined in 3.40 is being used in place of rated speed to run the test cycle then this speed may be used in place of rated speed when setting the charge air temperature.

The objective is to produce emission results that are representative of in-use operation. If good engineering judgment indicates that the specifications in this clause would result in unrepresentative testing (such as overcooling of the intake air), with the prior agreement of the parties involved more sophisticated set points and controls of charge-air pressure drop, coolant temperature, and flow rate may be used to achieve more representative results.

5.4 Engine exhaust system

5.4.1 General

The exhaust system installed with the engine or one that represents a typical in-use configuration shall be used. The exhaust system shall conform to the requirements for exhaust gas sampling, as set out in ISO 8178-1:2020, 5.2.1.

5.4.2 Exhaust restriction

An engine exhaust system or a test laboratory system shall be used presenting a static exhaust backpressure within 80 % to 100 % of the maximum exhaust restriction specified by the manufacturer at the rated speed and full load. The restriction may be set using a valve. If the maximum restriction is 5 kPa or less, the set point shall not be more than 1,0 kPa from the maximum.

When the maximum test speed (MTS) defined in 3.40 is being used in place of rated speed to run the test cycle then this speed may be used in place of rated speed when setting the exhaust restriction.

5.4.3 Engine with exhaust after-treatment system

If the engine is equipped with an exhaust after-treatment system, the exhaust pipe shall have the same diameter as found in-use, or as specified by the manufacturer, for at least four pipe diameters upstream of the expansion section containing the after-treatment device. The distance from the exhaust manifold flange or turbocharger outlet to the exhaust after-treatment system shall be the same as in the in-use configuration or within the distance specifications of the manufacturer. Where other installation requirements are specified by the manufacturer these shall also be respected for the test configuration.

The exhaust restriction shall be set according to 5.4.2. For variable-restriction after-treatment devices, the maximum exhaust restriction used in 5.4.2 is defined at the after-treatment condition (degreening/ageing and regeneration/loading level) specified by the manufacturer. The after-treatment container may be removed during dummy tests and during engine mapping, and replaced with an equivalent container having an inactive catalyst support.

5.5 Specific test conditions

5.5.1 Engine with exhaust after-treatment system

The emissions measured on the test cycle shall be representative of the emissions in the field.

5.5.1.1 Use of reagent

In the case of an engine equipped with an exhaust after-treatment system that requires the consumption of a reagent, the reagent used for all tests shall be declared by the manufacturer.

5.5.1.2 Regeneration

For engines equipped with exhaust after-treatment systems that are regenerated on an infrequent (periodic) basis, as described in 5.5.1.2.2, emission results shall be adjusted to account for regeneration events. In this case, the average emission depends on the frequency of the regeneration event in terms of fraction of tests during which the regeneration occurs. After-treatment systems with continuous regeneration according to 5.5.1.2.1 do not require a special test procedure.

If the exhaust aftertreatment has a security mode that works on an infrequent (periodic) regeneration mode, it shall be checked according to 5.5.1.2.2. For that specific case, the applicable emission limits could be exceeded and the measured emissions would not be weighted.

5.5.1.2.1 Continuous regeneration

For an exhaust aftertreatment system based on a continuous regeneration process, the emissions shall be measured on an aftertreatment system that has been stabilized so as to result in repeatable emissions behaviour. The regeneration process shall occur at least once during the NRTC hot start test, LSI-NRTC or NRSC test, and the manufacturer shall declare the normal conditions under which regeneration occurs (soot load, temperature, exhaust back-pressure, etc.). In order to demonstrate that the regeneration process is continuous, at least three NRTC hot start tests, LSI-NRTC or NRSC tests shall be conducted. In case of NRTC hot start test, the engine shall be warmed up in accordance with 8.4.2, the engine shall be soaked according to 8.6.3 and the first NRTC hot start test run. The subsequent NRTC hot start tests shall be started after soaking according to 8.6.3. During the tests, exhaust temperatures and pressures shall be recorded (temperature before and after the after-treatment system, exhaust back pressure, etc.). The aftertreatment system is considered to be satisfactory if the conditions declared by the manufacturer occur during the test during a sufficient time and the emission results do not scatter by more than ±25 % from the mean value or 0,005 g/kWh, whichever is greater. PN emissions do not need to meet the specified scatter requirement if gaseous and PM emissions meet this requirement. If the exhaust aftertreatment has a security mode that shifts to an infrequent (periodic) regeneration mode, it shall be checked according to 5.5.1.2.2. For that specific case, the applicable emission limits could be exceeded and would not be weighted.

5.5.1.2.2 Infrequent (periodic) regeneration

This provision only applies for engines equipped with emission controls that are regenerated on a periodic basis.

Testing and development of adjustment factors is only required for one applicable transient (NRTC or LSI-NRTC) or RMC test cycle. The factors that have been developed may be applied to results from the other applicable test cycles including discrete-mode NRSC.

In case that no suitable adjustment factors are available from testing using transient or RMC test cycles then adjustment factors shall be established using an applicable discrete-mode test. Factors developed using a discrete-mode test cycle shall only be applied to discrete-mode test cycles.

It shall not be required to conduct testing and develop adjustment factors on both RMC and discrete-mode NRSCs.

5.5.1.2.2.1 Requirement for establishing adjustment factors using NRTC, LSI-NRTC or RMC NRSC testing

The emissions shall be measured on at least three NRTC hot start tests, LSI-NRTC or ramped-modal cycle (RMC) NRSC tests, one with and two without a regeneration event on a stabilized aftertreatment system. The regeneration process shall occur at least once during the NRTC, LSI-NRTC or RMC NRSC test with a regeneration event. If regeneration takes longer than one NRTC, LSI-NRTC or RMC NRSC test, consecutive NRTC, LSI-NRTC or RMC NRSC tests shall be run and emissions continued to be measured without shutting the engine off until regeneration is completed and the average of the tests shall be calculated. If regeneration is completed during any test, the test shall be continued over its entire length.

An appropriate adjustment factor shall be determined for the entire applicable cycle using Formulae (5) to (8).

5.5.1.2.2.2 Requirement for establishing adjustment factors using discrete-mode NRSC testing

Starting with a stabilized after-treatment system the emissions shall be measured on at least three runs of each test mode of the applicable discrete-mode NRSC on which the conditions for regeneration can be met, one with and two without a regeneration event. The measurement of PM shall be conducted using the multiple filter method. If regeneration has started but is not complete at the end of the sampling period for a specific test mode extend the sampling period until regeneration is complete. Where there are multiple runs for the same mode an average result shall be calculated. The process shall be repeated for each test mode.

An appropriate adjustment factor shall be determined using Formulae (5) to (8) for those modes of the applicable cycle for which regeneration occurs.

5.5.1.2.2.3 General procedure for developing infrequent regeneration adjustment factors (IRAFs)

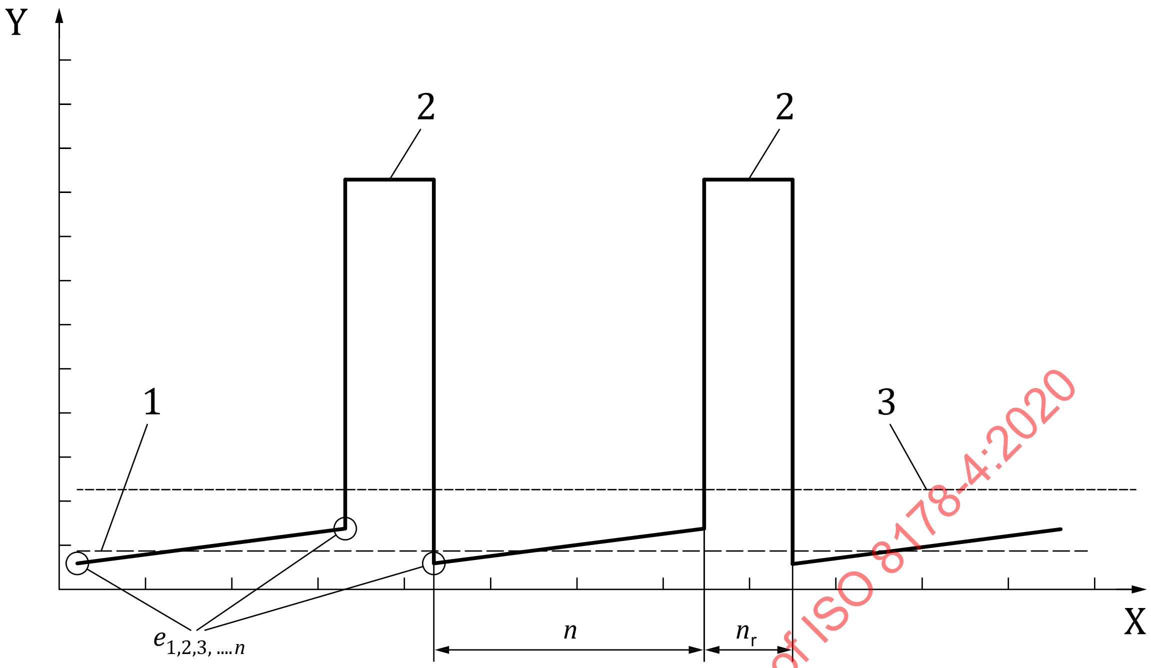
The engine may be equipped with a switch capable of preventing or permitting the regeneration process provided this operation has no effect on the original engine calibration.

The manufacturer shall declare the normal parameter conditions under which the regeneration process occurs (soot load, temperature, exhaust back pressure, etc.). The manufacturer shall also provide the frequency of the regeneration event in terms of number of tests during which the regeneration occurs. The exact procedure to determine this frequency shall be agreed by the parties involved based upon good engineering judgement.

For a regeneration test, the manufacturer shall provide an aftertreatment system that has been loaded. Regeneration shall not occur during this engine conditioning phase. As an option, the manufacturer may run consecutive tests of the applicable cycle until the aftertreatment system is loaded. Emissions measurement is not required on all tests.

Average emissions between regeneration phases shall be determined from the arithmetic mean of several approximately equidistant tests of the applicable cycle. As a minimum, at least one applicable cycle as close as possible prior to a regeneration test and one applicable cycle immediately after a regeneration test shall be conducted.

During the regeneration test, all the data needed to detect regeneration shall be recorded (CO or NO_x emissions, temperature before and after the after-treatment system, exhaust back pressure, etc.). During the regeneration process, the applicable emission limits may be exceeded. The test procedure is schematically shown in Figure 2.



Key

X number of test cycles

Y emissions (g/kWh or #/kWh)

1 mean emissions during sampling $e_{1,2,3,...n}$

2 emissions during regeneration e_r

3 weighted emissions of sampling and regeneration e_w

n number of tests cycles in which regeneration does not occur

n_r number of tests cycles in which regeneration occurs (minimum one test)

Figure 2 — Scheme of infrequent (periodic) regeneration with n number of measurements and n_r number of measurements during regeneration

The average specific emission rate related to the test runs conducted according to 5.5.1.2.2.1 or 5.5.1.2.2.2 [g/kWh or #/kWh] shall be weighted as follows (see Figure 2):

$$\bar{e}_w = \frac{n \cdot \bar{e} + n_r \cdot \bar{e}_r}{n + n_r} \tag{4}$$

where

n is the number of tests in which regeneration does not occur;

n_r is the number of tests in which regeneration occurs (minimum one test);

$\bar{e}_w$ is the average specific emission from a test in which the regeneration does not occur [g/kWh or #/kWh];

$\bar{e}_r$ is the average specific emission from a test in which the regeneration occurs [g/kWh or #/kWh].

At the choice of the manufacturer and based on upon good engineering analysis, the regeneration adjustment factor k_r, expressing the average emission rate, may be calculated either multiplicative or additive for all gaseous pollutants, and, where there is an applicable limit for PM and PN, as follows:

— **Multiplicative**

$$k_{\text{MUr}} = \frac{\bar{e}_{\text{w}}}{\bar{e}} \text{ (upward adjustment factor)} \tag{5}$$

$$k_{\text{MDr}} = \frac{\bar{e}_{\text{w}}}{\bar{e}_{\text{r}}} \text{ (downward adjustment factor)} \tag{6}$$

— **Additive**

$$k_{\text{Ur}} = \bar{e}_{\text{w}} - \bar{e} \text{ (upward adjustment factor)} \tag{7}$$

$$k_{\text{Dr}} = \bar{e}_{\text{w}} - \bar{e}_{\text{r}} \text{ (downward adjustment factor)} \tag{8}$$

Upward adjustment factors are multiplied with or added to measured emission rates for all tests in which the regeneration does not occur. Downward adjustment factors are multiplied with or added to measured emission rates for all tests in which the regeneration occurs. The occurrence of the regeneration shall be identified in a manner that is readily apparent during all testing. Where no regeneration is identified, the upward adjustment factor shall be applied.

With reference to Clause 9 and Annex H on brake specific emission calculations, the regeneration adjustment factor:

a) When established for an entire weighted cycle, shall be applied to the results of the applicable weighted NRTC, LSI-NRTC and NRSC tests;

b) When established specifically for the individual modes of the applicable discrete-mode cycle, shall be applied to the results of those modes of the applicable discrete-mode NRSC cycle for which regeneration occurs prior to calculating the cycle weighted emission result. In this case the multiple filter method shall be used for PM measurement;

c) May be extended to other members of the same engine family;

d) May be extended to other engine families within the same engine aftertreatment system family with the prior approval of the parties involved based on technical evidence to be supplied by the manufacturer that the emissions are similar.

The following options shall be considered:

a) A manufacturer may elect to omit adjustment factors for one or more of its engine families (or configurations) because the effect of the regeneration is small, or because it is not practical to identify when regenerations occur. In these cases, no adjustment factor shall be used, and the manufacturer is liable for compliance with the emission limits for all tests, without regard to whether a regeneration occurs.

b) Upon request by the manufacturer, the parties involved may account for regeneration events differently than is provided in a). However, this option only applies for events that occur extremely infrequently, and which cannot be practically addressed using the adjustment factors described in a).

5.5.2 Crankcase emissions

Where the parties involved require crankcase emissions that are normally discharged to ambient atmosphere to be included, the emissions shall be added to the exhaust emissions during all emission testing either

a) physically, or

b) mathematically.

When using method a), manufacturers shall install the engines on the test-bed in a manner that all crankcase emissions are routed into the exhaust system as described in this clause. For the purpose of this clause, crankcase emissions that are routed into the exhaust upstream of exhaust after-treatment during all operation are not considered to be discharged directly into the ambient atmosphere.

Open crankcase emissions shall be routed into the exhaust system for emission measurement, as follows:

c) The tubing materials shall be smooth-walled, electrically conductive, and not reactive with crankcase emissions. Tube lengths shall be minimized as far as possible. The tube may optionally be heated or thin-walled or insulated with an air-gap to minimize temperature differences between the wall and the crankcase emissions constituents.

d) The number of bends in the laboratory crankcase tubing shall be minimized, and the radius of any unavoidable bend shall be maximized.

e) The laboratory crankcase exhaust tubing shall meet the engine manufacturer's specifications for crankcase back pressure.

f) The crankcase exhaust tubing shall connect into the raw exhaust downstream of any aftertreatment system, downstream of any installed exhaust restriction, and sufficiently upstream of any sample probes to ensure complete mixing with the engine's exhaust before sampling. The crankcase exhaust tube shall extend into the free stream of exhaust to avoid boundary-layer effects and to promote mixing. The crankcase exhaust tube's outlet may orient in any direction relative to the raw exhaust flow.

Method b) is permitted with the prior approval of the parties involved.

5.6 Cooling system

An engine cooling system with sufficient capacity to maintain the engine, with its intake-air, oil, coolant, block and head temperatures, at normal operating temperatures prescribed by the manufacturer shall be used. Laboratory auxiliary coolers and fans may be used.

5.7 Lubricating oil

The lubricating oil shall be specified by the manufacturer and be representative of lubricating oil available in the market; the specifications of the lubricating oil used for the test shall be recorded and presented with the results of the test.

6 Test fuels

Fuel characteristics influence the engine exhaust gas emission. Therefore, the characteristics of the fuel used for the test should be determined, recorded and presented with the results of the test. Where fuels designated in ISO 8178-5 as reference fuels are used, the reference code and the analysis of the fuel shall be provided. For all other fuels the characteristics to be recorded are those listed in the appropriate universal data sheets in ISO 8178-5. See Table 2.

Table 2 — Selection of fuel

Test purpose	Interested parties	Fuel selection
Type approval (Certification)	1. Certification body 2. Manufacturer or supplier	Reference fuel, if one is defined Commercial fuel if no reference fuel is defined
Acceptance test	1. Manufacturer or supplier 2. Customer or inspector	Commercial fuel as specified by the manufacturer[a]

[a] Customers and inspectors should note that the emission tests carried out using commercial fuel will not necessarily comply with limits specified when using reference fuels.

Table 2 *(continued)*

Test purpose	Interested parties	Fuel selection
Research/development	One or more of: Manufacturer, research organization, fuel and lubricant supplier, etc.	To suit the purpose of the test

[a] Customers and inspectors should note that the emission tests carried out using commercial fuel will not necessarily comply with limits specified when using reference fuels.

7 Test cycles

7.1 General

The following duty cycles are described in this clause: discrete mode steady-state cycles, ramped-modal steady-state cycles and transient cycle. The cycles and their applicability are described in 7.5 (steady-state) and 7.6 (transient), while the method to determine the appropriate test points (speed, torque, power) are described in 7.2 to 7.4. The tabulated cycles are contained in Annex A to Annex C.

7.2 Test speeds

Test speeds shall be determined according to the test cycle(s) to be used. In certain cases a rated speed will be used to represent 100 % speed, as declared by the manufacturer according to 3.58. In other cases the MTS (maximum test speed) will be used to represent 100 % speed, as determined from the curve of engine speed versus power according to 7.2.1. Where applicable, an intermediate speed will be determined according to 3.34. Where intermediate speed is not used the other speeds will be determined as a percentage of the rated speed or MTS.

For constant-speed engines the 100 % speed shall be determined according to 7.2.5.

7.2.1 Maximum test speed (MTS)

For engines that are tested with a transient cycle the MTS shall be determined according to this clause. In this case the 100 % test speed is equal to the MTS. For engines that are tested with both a steady state cycle (discrete- or ramped- modal) and also a transient cycle, the MTS shall also be used in place of the rated speed for operating the steady state cycle.

7.2.1.1 Calculation of MTS

In order to calculate the MTS for variable-speed engines the transient mapping procedure shall be performed according to 7.4. The MTS is then determined from the mapped values of engine speed versus power. For the calculation of the MTS one of the following formulations shall be used:

a) $$n_{MTS} = n_{lo} + 0{,}95 \cdot (n_{hi} - n_{lo}) \quad (9)$$

where

n_{hi} is high speed (see 3.31);

n_{lo} is low speed (see 3.37).

b) $n_{MTS} = n_i$ at the average of the lowest and highest speeds at which $(n^2_{normi} + P^2_{normi})$ is equal to 98 % of the maximum value of $(n^2_{normi} + P^2_{normi})$. If there is only one speed at which the value of $(n^2_{normi} + P^2_{normi})$ is equal to 98 % of the maximum value of $(n^2_{normi} + P^2_{normi})$ then MTS = ni at which the maximum value of $(n^2_{normi} + P^2_{normi})$ occurs. (10)

where

n is engine speed;

i is an indexing variable that represents one recorded value of an engine map;

$n_{\text{norm}i}$ is an engine speed normalized by dividing it by $n_{P\text{max}}$;

$P_{\text{norm}i}$ is an engine power normalized by dividing it by P_{max};

$n_{P\text{max}}$ is the average of the lowest and highest speeds at which power is equal to 98 % of P_{max}. Linear interpolation shall be used between the mapped values to determine the speeds where power is equal to 98 % of P_{max}. If there is only one speed at which power is equal to 98 % of P_{max} then $n_{P\text{max}}$ shall be the speed at P_{max}.

Linear interpolation shall be used between the mapped values to determine the speeds where ($n^2_{\text{norm}i}$ + $P^2_{\text{norm}i}$) is equal to 98 % of the maximum value of ($n^2_{\text{norm}i}$ + $P^2_{\text{norm}i}$).

7.2.1.2 Use of a declared MTS

If the MTS calculated according to 7.2.1.1 is within ±3 % of the MTS declared by the manufacturer, the declared MTS may be used for the emissions test. If the tolerance is exceeded, the calculated MTS shall be used for the emissions test.

7.2.1.3 Use of an adjusted MTS for correct driving of the NRTC

If the falling part of the full load curve has a very steep edge, this may cause problems to drive the 105 % speeds of the NRTC test cycle correctly. In this case it is allowed, with prior agreement of the parties involved, to use an alternative value of MTS determined using one of the following methods:

a) Reduce the MTS slightly (maximum 3 %) in order to make correct driving of the NRTC possible.

b) Calculate an alternative MTS using the following formulation:

$$n_{\text{MTS}} = \left(n_{\text{max}} - n_{\text{idle}}\right)/1{,}05 + n_{\text{idle}} \qquad (11)$$

where

n_{max} is maximum no load speed;

n_{idle} is idle speed.

7.2.2 Rated speed

The rated speed is defined in 3.58 and will normally be the maximum full load speed allowed by the governor, as designed by the manufacturer, or, if such a governor is not present, the speed at which the maximum power is obtained from the engine, as designed by the manufacturer.

For variable-speed engines that are not tested with a transient cycle the 100 % test speed is equal to the rated speed.

At manufacturers' discretion, maximum test speed may be used instead of rated speed for any steady state test cycle.

7.2.3 Intermediate speed

The maximum torque speed used for the determination of intermediate speed shall be obtained from the maximum torque curve established from the engine mapping conducted according to one of the procedures in 7.4.

The maximum torque speed is either:

a) the speed at which the highest torque was recorded; or

b) the average of the lowest and highest speeds at which the torque is equal to 98 % of the maximum torque. Where necessary, linear interpolation shall be used to determine the speeds at which the torque is equal to 98 % of the maximum.

If the maximum torque speed determined from the maximum torque curve is within ±4 % of the maximum torque speed declared by the manufacturer for SI engines <56 kW, or ±2,5 % of the maximum torque speed declared by the manufacturer for all other engines, the declared value may be used. If the tolerance is exceeded, the maximum torque speed determined from the maximum torque curve shall be used.

The intermediate speed shall meet one of the following requirements:

a) For engines that are designed to operate over a speed range on a full load torque curve, the intermediate speed shall be the maximum torque speed if it occurs between 60 % and 75 % of rated speed.

b) If the maximum torque speed is less than 60 % of rated speed, then the intermediate speed shall be 60 % of the rated speed.

c) If the maximum torque speed is greater than 75 % of the rated speed then the intermediate speed shall be 75 % of rated speed. Where the engine is only capable of operation at speeds higher than 75 % of rated speed the intermediate speed shall be the lowest speed at which the engine can be operated.

d) For engines that are not designed to operate over a speed range on a full-load torque curve at steady-state conditions, the intermediate speed will typically be between 60 % and 70 % of the rated speed.

e) For engines to be tested on cycle G1, the intermediate speed shall be 85 % of the rated speed.

In the case that the maximum test speed (MTS) is used in place of rated speed for the 100 % test speed, MTS shall also replace rated speed when determining the intermediate speed.

7.2.4 Idle speed

The idle speed is the lowest engine speed with minimum load (greater than or equal to zero load), where an engine governor function controls engine speed. For engines without a governor function that controls idle speed, idle speed means the manufacturer-declared value for lowest engine speed possible with minimum load. Note that warm idle speed is the idle speed of a warmed-up engine.

7.2.5 Test speed for constant-speed engines

The governors of constant-speed engines may not always maintain speed exactly constant. Typically, speed can decrease (0,1 to 10) % below the speed at zero load, such that the minimum speed occurs near the engine's point of maximum power. The test speed for constant-speed engines may be commanded by using the governor installed on the engine or using a test-bed speed demand where this represents the engine governor.

Where the governor installed on the engine is used the 100 % speed shall be the engine governed speed.

Where a test-bed speed demand signal is used to simulate the governor, the 100 % speed at zero load shall be the no load speed specified by the manufacturer for that governor setting and the 100 % speed at full load shall be the rated speed for that governor setting. Interpolation shall be used to determine the speed for the other test modes.

In the case that the governor has an isochronous operation setting, or the nominal rated speed and no-load speed declared by the manufacturer differ by no more than 3 %, a single value declared by the manufacturer may be used for the 100 % speed at all load points.

7.3 Torque and power

7.3.1 Torque

The torque figures given in the test cycles are percentage values that represent, for a given test mode, one of the following:

a) The ratio of the required torque to the maximum possible torque at the specified test speed (all cycles except D1, D2, E2, E4).

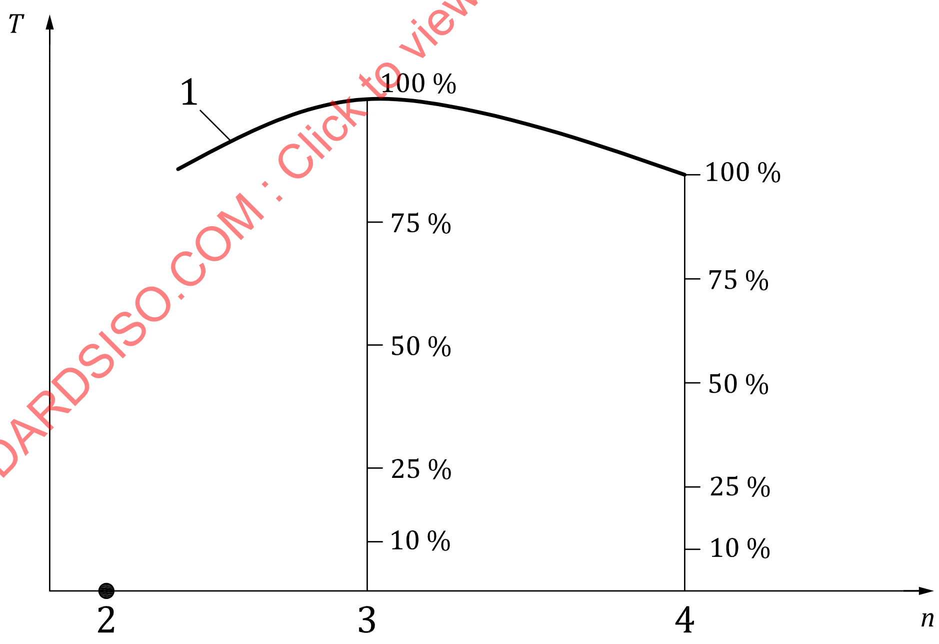
b) The ratio of the required torque to the torque corresponding to the continuous rated power (cycle D1) declared by the manufacturer as defined in ISO 8528-1.

c) The ratio of the required torque to the torque corresponding to the rated power declared by the manufacturer as defined in ISO 8528-1 (cycle D2).

d) For cycle E2 % torque is relative to the torque corresponding to the rated power declared by the manufacturer.

e) For the test cycle E4 the torque figures are percentage values of the torque at rated power. This cycle is based on the theoretical propeller characteristic curve representing typical pleasure craft spark-ignition engine operation.

Figure 3 shows torque scales for engines operating on a non-propeller curve.



Key

T torque

n engine speed

1 full-load torque curve

2 low idle

3 intermediate speed

4 100 % speed

Figure 3 — Torque scales: Percentage of full-load torque at each engine speed

7.3.2 Power

The power figures given in the test cycles are percentage values that represent, for a given test mode, one of the following:

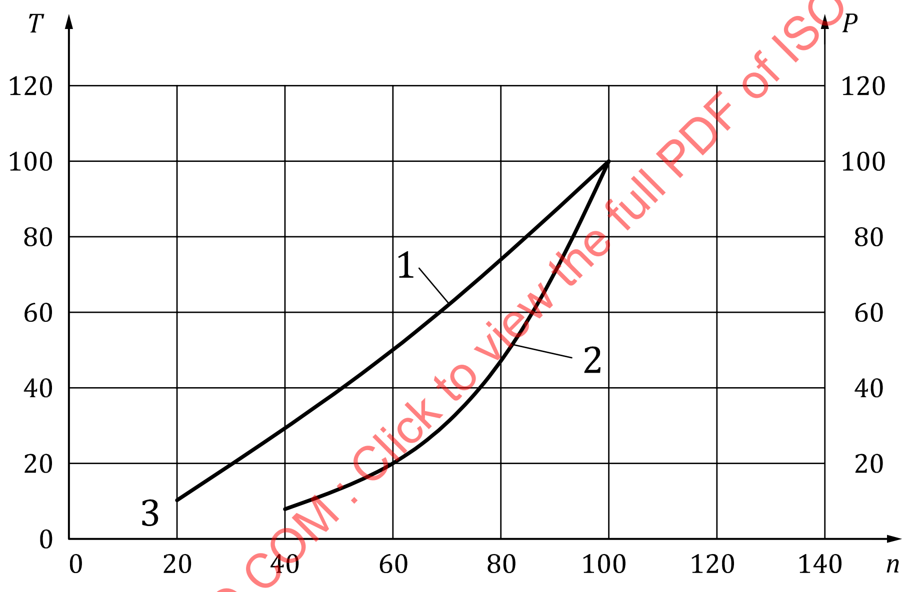
a) For the test cycle E3 the power figures are percentage values of the maximum rated power at the 100 % speed as this cycle is based on a theoretical propeller characteristic curve for vessels driven by heavy-duty engines without limitation of length.

b) For the test cycle E5 the power figures are percentage values of the maximum rated power at the 100 % speed as this cycle is based on a theoretical propeller characteristic curve for vessels of less than 24 m in length driven by diesel engines.

c) For the test cycle F the power figures are percentage values of the maximum power at the given test speed, except for idle speed where it is a percentage of the maximum rated power at the 100 % speed.

Figure 4 shows an example of two representative propeller curves.

NOTE Other propeller characteristic curves exist.



Key

T torque

n engine speed

P power

1 torque E4

2 power E3

3 idling

NOTE The values of *n*, *T* and *P* are expressed in % of rated speed, maximum torque and maximum power respectively.

Figure 4 — Examples of torque and power scales for propeller curves

7.4 Engine mapping

Before starting the engine mapping, the engine shall be warmed up and towards the end of the warm up it shall be operated for at least 10 min at maximum power or according to the recommendation of the manufacturer and good engineering judgement in order to stabilize the engine coolant and lube oil temperatures. When the engine is stabilized, the engine mapping shall be performed.

Except constant-speed engines, engine mapping shall be performed with fully open fuel lever or governor using discrete speeds in ascending order. The minimum and maximum mapping speeds are defined as follows:

— Minimum mapping speed = warm idle speed;

— Maximum mapping speed = n_{hi} × 1,02 or speed where max torque drops off to zero, whichever is smaller.

where n_{hi} is high speed (see 3.31).

If the highest speed is unsafe or unrepresentative (e.g. for ungoverned engines), good engineering judgement shall be used to map up to the maximum safe speed or the maximum representative one.

7.4.1 Engine mapping for transient cycles

The engine mapping shall be performed according to the following procedure:

a) The engine shall be unloaded and operated at idle speed.

   1) For engines with a low-speed governor, the operator demand shall be set to the minimum, the dynamometer or another loading device shall be used to target a torque of zero on the engine's primary output shaft and the engine shall be allowed to govern the speed. This warm idle speed shall be measured.

   2) For engines without a low-speed governor, the dynamometer shall be set to target a torque of zero on the engine's primary output shaft, and the operator demand shall be set to control the speed to the manufacturer-declared lowest engine speed possible with minimum load (also known as manufacturer-declared warm idle speed).

   3) The manufacturer declared idle torque may be used for all variable-speed engines (with or without a low-speed governor), if a nonzero idle torque is representative of in-use operation.

b) Operator demand shall be set to maximum and engine speed shall be controlled to between warm idle and 95 % of its warm idle speed. For engines with reference duty cycles, which lowest speed is greater than warm idle speed, the mapping may be started at between the lowest reference speed and 95 % of the lowest reference speed.

c) The engine speed shall be increased at an average rate of (8 ± 1) min^{-1}/s or the engine shall be mapped by using a continuous sweep of speed at a constant rate such that it takes 4 min to 6 min to sweep from minimum to maximum mapping speed. The mapping speed range shall be started between warm idle and 95 % of warm idle and ended at the highest speed above maximum power at which less than 70 % of maximum power occurs. If this highest speed is unsafe or unrepresentative (e.g. for ungoverned engines), good engineering judgment shall be used to map up to the maximum safe speed or the maximum representative speed. Engine speed and torque points shall be recorded at a sample rate of at least 1 Hz.

d) If a manufacturer believes that the above mapping techniques are unsafe or unrepresentative for any given engine, alternate mapping techniques may be used. These alternate techniques shall satisfy the intent of the specified mapping procedures to determine the maximum available torque at all engine speeds achieved during the test cycles. Deviations from the mapping techniques specified in this clause for reasons of safety or representativeness shall be approved by the parties involved along with the justification for their use. In no case, however, the torque curve shall be run by descending engine speeds for governed or turbocharged engines.

e) An engine need not be mapped before each and every test cycle. An engine shall be remapped if:

   1) an unreasonable amount of time has transpired since the last map, as determined by good engineering judgement; or

2) physical changes or recalibrations have been made to the engine which potentially affect engine performance; or

3) the atmospheric pressure near the engine's air inlet is not within ±5 kPa of the value recorded at the time of the last engine map.

7.4.2 Engine mapping for variable-speed steady-state cycles

In the case of engine mapping for a steady-state cycle (only for engines which have not to run a transient cycle), good engineering judgment shall be used to select a sufficient number of evenly spaced set-points. At each set-point, speed shall be stabilized and torque allowed to stabilize for at least 15 s. The mean speed and torque shall be recorded at each set-point. Where feasible the mean speed and torque should be calculated using the recorded data from the last 4 s to 6 s. Linear interpolation shall be used to determine the steady-state test speeds and torques if needed.

Except as set-out in 7.2, if the derived test speeds and torques do not deviate for more than ±3 % from the speeds and torques indicated by the manufacturer, the manufacturer defined speeds and torques shall be applied. When engines are additionally required to run a transient cycle, then the transient mapping curve shall be used to determine steady-state test speeds and torques.

At the choice of the manufacturer the engine mapping may alternatively be conducted according to the procedure in 7.4.1.

7.4.3 Engine mapping for constant-speed engines

The engine may be operated with a production constant-speed governor or a constant-speed governor maybe simulated by controlling engine speed with an operator demand control system. Either isochronous or speed-droop governor operation shall be used, as appropriate.

The following mapping procedure shall be applied:

a) With the governor or simulated governor controlling speed using operator demand, the engine shall be operated at no-load governed speed (at high speed, not low idle) for at least 15 s, unless the specific engine is unable to perform this task.

b) The dynamometer shall be used to increase torque at a constant rate. The map shall be conducted such that it takes no less than 2 min to sweep from no-load governed speed to the torque corresponding to rated power for engines to be tested on cycle D1, D2 or E2 or to maximum torque in the case of other constant-speed test cycles. During the engine mapping actual speed and torque shall be recorded with at least 1 Hz;

c) In case of a constant-speed engine with a governor that can be reset to alternative speeds, the engine shall be tested at each applicable constant speed.

d) For constant-speed engines good engineering judgment shall be used to apply other methods to record torque corresponding to rated power at the defined operating speed(s). Other suitable methods shall include but not be limited to the following:

   1) For constant-speed engines subject only to steady-state testing, an engine map may be performed by using a series of discrete torques. At least five evenly spaced torque setpoints from no-load to 80 % of the manufacturer-declared test torque or to a torque derived from the published maximum power level shall be selected if the declared test torque is not available. Starting at the 80 % torque point, setpoints in 2,5 % or smaller intervals are selected, stopping at the endpoint torque. The endpoint torque is defined as the first discrete mapped torque value greater than the torque at maximum observed power where the engine outputs 90 % of the maximum observed power; or the torque when engine stall has been determined. Torque and speed shall be allowed to stabilize at each setpoint and the mean feedback speed and torque at each setpoint shall be recorded. Mapping at higher torque setpoints may be carried out if desired. From this series of mean feedback speed and torque values, intermediate values are

determined by using linear interpolation. These series of mean speeds and torques are used to generate the power map.

2) For any constant-speed engine, an engine map may be performed with a continuous torque sweep by continuing to record the mean feedback speed and torque at 1 Hz or higher frequency. The reference torque shall be increased by the dynamometer at a constant rate from no-load to the endpoint torque. The torque sweep rate is targeted to be equal to the manufacturer-declared test torque (or a torque derived from the published power level) divided by 180 s. It shall be verified, that the average torque sweep rate over the entire map is within ±7 % of the target torque sweep rate. From this series of mean feedback speed and torque values, intermediate values are determined by using linear interpolation. These series of mean speeds and torques are used to generate the power map.

3) For any isochronous governed (0 % speed droop) constant-speed engine, the engine may be mapped with two points. After stabilizing at the no-load governed speed, the mean feedback speed and torque is recorded.

The engine shall be operated with the governor or simulated governor controlling engine speed using operator demand, and the dynamometer shall be used to target a speed of 99,5 % of the recorded mean no-load governed speed. Torque and speed shall be allowed to stabilize at each setpoint. The mean feedback speed and torque at each setpoint and the target speed shall be recorded.

The absolute value of the speed error (the mean feedback speed minus the target speed) must be no greater than 0,1 % of the recorded mean no-load governed speed. From this series of mean feedback speed and torque values, intermediate values are determined by using linear interpolation. These series of two mean feedback speeds and torques are used to generate the power map. Note that the measured maximum test torque will be the mean feedback torque recorded on the second point.

For engines tested on cycles other than D1, D2 or E2, when both measured and declared values are available for the maximum torque, the declared value may be used instead of the measured value if it is within 95 to 100 % of the measured value.

7.5 Steady-state test cycles

Steady-state test cycles are specified as a list of discrete modes (operating points), where each operating point has one value of speed and one value of torque. A steady-state test cycle shall be measured with a warmed up and running engine according to manufacturer's specification.

At the choice of the manufacturer, a steady-state test cycle may be run as a discrete-mode cycle or a ramped-modal cycle (RMC), as explained in 7.5.1 and 7.5.2.

Performing an RMC emission test according to 7.5.2 shall be optional. There may be technical reasons why an engine may not be able to operate according to the test cycles in 7.5.2. It shall not be required to conduct an emission test according to both 7.5.1 and 7.5.2.

7.5.1 Discrete mode test cycles

7.5.1.1 General remarks

The exhaust emission measurement and evaluation shall be carried out using the appropriate test cycle for the application as described in general in 7.5.3. The corresponding test cycles are tabulated in Annex A.

The particulate emission may be measured by either the multiple filter or the single filter method according to ISO 8178-1:2020, 8.6.1.2. To evaluate the particulate emission by the multiple filter method, it is necessary to measure the particulate concentration and the particulate mass emission of each test mode at stabilized engine operation. The time needed for stabilization of the engine depends on engine size and ambient conditions.

7.5.1.2 Requirements for conduct of test using discrete mode cycle

7.5.1.2.1 Test sequence

Each test shall be performed with a warmed-up and running engine in the given sequence of the test modes for a particular test cycle.

7.5.1.2.2 Mode length

The minimum test mode length is 10 min, which is the standard, except when testing spark-ignition engines using cycles "G". If necessary the mode length may be extended e.g. to collect sufficient particulate sample mass or to achieve stabilization with large engines.

For spark-ignition engines when only gaseous emissions are measured using cycles "G", each mode time shall be at least 3 min.

The mode length shall be recorded and reported.

7.5.1.2.3 Emission measurement

Except when testing spark-ignition engines using test cycles "G", the gaseous exhaust emission concentration values shall be measured and recorded for at least 3 min anywhere in the mode if the engine is stabilized and meets the speed and torque requirements of the respective mode.

For spark-ignition engines when only gaseous emissions are measured using cycles "G", the gaseous exhaust emission concentration values shall be measured and recorded for the last 2 min of the respective test mode.

Only the last 60 s of the measurement period shall be used for emission calculation in accordance with Clause 9 or Annex H.

Particulate sampling shall not commence before engine stabilization, as defined by the manufacturer, has been achieved, and shall preferably be conducted at the same time as gaseous emissions are measured. For the single filter method, the completion of particulate sampling shall be within ±5 s of the completion of the gaseous emission measurement.

7.5.1.2.4 Repeat measurements

For the multiple filter method only, particulate sampling and gaseous emissions measurement may be repeated during the mode until a valid sample is obtained as long as the speed and torque requirements are met.

Test modes may be repeated, as long as the engine is pre-conditioned by running the previous or current mode. In the case of the first mode of any cycle, the engine shall be preconditioned according to 8.4.2.

7.5.1.2.5 Validation criteria

During each mode of the given steady-state test cycle after the initial transition period, the measured speed shall not deviate from the reference speed for more than ±1 % of rated speed or ±3 min^{-1}, whichever is greater except for idle which shall be within the tolerances declared by the manufacturer. The measured torque shall not deviate from the reference torque for more than ±2 % of the maximum torque at the test speed.

7.5.1.2.6 Equipment malfunction

If at any time during a test mode, the test equipment malfunctions or the engine speed and load do not meet the requirements of 7.5.1.2.5, the test mode is void and may be aborted. The test mode may be restarted by preconditioning with the previous or current mode.

7.5.2 Ramped-modal test cycles

7.5.2.1 General remarks

An RMC is intended to provide a method for performing a steady-state test in a pseudo-transient manner. Each RMC consists of a series of steady state modes with a linear transition between them. The relative total time at each mode and its preceding transition match the weighting of the discrete mode steady state cycles. In some cases modes are not run in the same order as the discrete mode steady state cycles or are split to prevent extreme changes in temperature.

The exhaust emission measurement and evaluation shall be carried out using the appropriate test cycle for the application as described in general in 7.5.3. The corresponding test cycles are tabulated in Annex B. Where available the RMCs are numbered to correspond to the equivalent discrete mode cycle. Where no RMC exists for a given application the steady state test shall be conducted using the appropriate discrete mode cycle.

7.5.2.2 Requirements for conduct of test using RMC

7.5.2.2.1 Test sequence

Each test shall be performed with a warmed-up and running engine in the given sequence of the test modes for a particular test cycle.

7.5.2.2.2 Mode length

The engine shall be continuously controlled by the test bed control unit during the RMC test cycle. The mode length is defined in the respective table in Annex B. Advance from one mode to the next within a 20-second transition phase. During the transition phase, command a linear progression from the torque setting of the current mode to the torque setting of the next mode, and simultaneously command a similar linear progression for engine speed if there is a change in speed setting.

7.5.2.2.3 Emission measurement

The gaseous and particulate emissions shall be measured and sampled continuously during the RMC test cycle in the same way as in a transient cycle.

7.5.2.2.4 Repeat measurements

Due to the fact that emissions are measured continuously during the RMC test cycle, repeat measurements within the test cycle are not permitted.

In case of engine stall during the test the entire test is void and may be aborted. The entire test shall be restarted.

7.5.2.2.5 Equipment malfunction

If at any time during a test mode, the test equipment malfunctions or the engine speed and load do not meet the requirements of 7.5.1.2.5, the entire test is void and shall be aborted. The entire test shall be restarted.

7.5.3 Cycle types and applicability

This clause provides a general description of the test cycles for different engine applications.

7.5.3.1 Test cycles type C “Non-road machinery and industrial equipment”

7.5.3.1.1 Test cycle type C1 “Compression-ignition engine powered non-road machinery and industrial equipment”

General-purpose variable-speed test cycle. Tables of discrete and RMC test modes are listed in A.1 and B.1 respectively.

Typical examples of applications are:

— industrial drilling rigs, compressors etc.;

— construction equipment including wheel loaders, bulldozers, crawler tractors, crawler loaders, truck-type loaders, dumpers, hydraulic excavators etc.;

— agricultural equipment, rotary tillers;

— forestry equipment;

— self-propelled agricultural vehicles (including tractors);

— material handling equipment;

— fork-lift trucks;

— road maintenance equipment (graders, road rollers, asphalt finishers);

— snow plough equipment;

— snow tractors;

— airport supporting equipment;

— aerial lifts;

— mobile cranes.

This list is not exhaustive.

NOTE 1 Compression-ignition engines with rated power typically below 19 kW intended for applications listed under 7.5.3.5 (test cycles G), can be tested according to the test cycles given in 7.5.3.1 (test cycles C).

NOTE 2 Compression-ignition engines that operate within ±15 % of the rated speed and spend less than 15 % of their time at idle speed can be tested according to test cycle D2.

This test cycle may optionally be used for spark-ignition engines >56 kW.

7.5.3.1.2 Cycle C2 “Spark-ignition engine powered non-road machinery and industrial equipment”, >19 kW

Variable-speed test cycle with focus on intermediate speed operation. Tables of discrete and RMC test modes are listed in A.1 and B.1 respectively.

Typical examples of applications are:

— fork-lift trucks;

— airport supporting equipment;

— material handling equipment;

— road maintenance equipment;

— agricultural equipment.

This list is not exhaustive.

Test cycle C1 may optionally be used for spark-ignition engines >56 kW.

7.5.3.2 Test cycles type D "Constant speed"

Test cycles for engine applications where the load is driven at constant speed. Tables of discrete and RMC test modes are listed in A.2 and B.2 respectively.

Typical examples of applications are:

- cycle D1:
  - power plants;
- cycle D2:
  - gas compressors;
  - irrigation pumps;
  - generating sets with intermittent load including generating sets on board of ships and trains (not for propulsion), welding sets;
  - turf care, chippers, snow removal equipment, sweepers.

This list is not exhaustive.

NOTE 1 Diesel engines with rated power typically below 19 kW intended for application listed under 7.5.3.5 (test cycles G) can be tested according to the test cycles given in 7.5.3.2 (test cycles D).

NOTE 2 Diesel engines that operate within ±15 % of the rated speed and spend less than 15 % of their time at idle speed can be tested according to test cycle D2.

7.5.3.3 Test cycles type E "Marine applications"

Test cycles for marine propulsion engines. Tables of discrete and RMC test modes are listed in A.3 and B.3 respectively.

Selection of test cycles shall conform to the following criteria:

- cycle E1: compression ignition engines for propulsion of craft less than 24 m in length except tug boats and push boats;
- cycle E2: constant-speed heavy duty engines for propulsion of ships of any length including diesel-electric drive and variable-pitch propeller applications;
- cycle E3: propeller-law heavy duty engines for propulsion of ships of any length;
- cycle E4: spark-ignition engines for propulsion of craft less than 24 m in length except tug boats and push boats;
- cycle E5: compression ignition engines for propulsion of craft less than 24 m in length when operated on a propeller law except for tug boats and push boats.

For compression ignition engines in craft less than 24 m in length, test cycle E1 or E5 can be applied depending on which cycle is closer to the actual operation.

For constant-speed marine propulsion engines cycle E2 applies. For variable pitch propeller sets cycle E2 or E3 may be used depending on which cycle is closer to the actual operation; usually the operation is closer to constant-speed operation (cycle E2).

For spark-ignition engines in craft less than 24 m in length test cycle E4 applies.

7.5.3.4 Test cycle type F "Rail traction"

Test cycle for rail propulsion. Tables of discrete and RMC test modes are listed in A.4 and B.4 respectively.

Typical examples of applications are:

— locomotives;

— rail cars;

— shunting locomotives.

This list is not exhaustive.

NOTE Diesel engines for railcars can be tested according to the cycle given in 7.5.3.1.1 (C1).

7.5.3.5 Test cycles type G "Utility, lawn and garden"; typically <19 kW

Tables of discrete and RMC test modes are listed in A.5 and B.5 respectively.

If the primary end use of an engine model is known then the test cycle may be chosen based on the examples given in 7.5.3.5. If the primary end use of an engine model is uncertain then the appropriate test cycle should be chosen based upon the engine specification. Both compression ignition and spark-ignition engines may be tested in any of the three cycles; whichever is most appropriate.

Typical examples of applications are:

- cycle G1:
  - pedestrian-controlled rotary or cylinder lawn mowers;
  - front or rear engine riding lawn mowers;
  - rotary tillers;
  - edge trimmers;
  - lawn sweepers;
  - waste disposers;
  - sprayers;
  - snow removal equipment;
  - golf carts;
- cycle G2:
  - portable generators, pumps, welders, air compressors;
  - may also include lawn and garden equipment that operates at engine-rated speed;
- cycle G3:
  - edge trimmers;
  - string trimmers;
  - blowers;
  - vacuum equipment;
  - chain saws;

— portable saw mills.

These lists are not exhaustive.

NOTE Diesel engines of any rated power intended for applications listed in other test cycles can be tested according to that cycle (e.g. cycles D and C1).

7.5.3.6 Test cycle type H “Snowmobile”

Test cycle for snowmobile engines. Tables of discrete and RMC test modes are listed in A.6 and B.6 respectively.

7.5.3.7 Test cycle type I “Transport refrigeration unit”

Test cycle for transport refrigeration unit applications that operate at two speeds. Tables of discrete and RMC test modes are listed in A.7 and B.7 respectively.

7.6 Transient cycles

7.6.1 General

Transient cycles are listed in Annex C as a second-by-second sequence of normalized speed and torque values. In order to perform the test on an engine test cell, the normalized values shall be converted to their equivalent reference values for the individual engine to be tested, based on specific speed and torque values identified in the engine mapping curve. The conversion is referred to as denormalization, and the resulting test cycle so developed as the reference cycle of the engine to be tested. With those reference speed and torque values, the cycle shall be run on the test cell, and the actual speed, torque and power values shall be recorded. In order to validate the test run, a regression analysis between reference and actual speed, torque and power values shall be conducted upon completion of the test. For calculation of the brake specific emissions, the actual cycle work shall be calculated by integrating actual engine power over the cycle. For cycle validation, the actual cycle work must be within prescribed limits of the cycle work of the reference cycle (reference cycle work).

7.6.2 Non-road transient cycle (NRTC)

The non-road transient cycle (NRTC) may be applied to variable-speed compression-ignition or spark-ignition engines for mobile use (NRMM) with a maximum power output between 19 kW and 560 kW that are also subject to the C1 steady-state (discrete- or ramped- modal) cycle. This cycle does not apply to non-road engines for applications that are not subject to the C1 test cycle.

The sequence of normalized speed and torque values is given in C.2.

7.6.2.1 Test sequence for NRTC

The transient test cycle shall be run twice after completion of pre-conditioning:

a) As cold start after the engine and aftertreatment systems have cooled down to room temperature after natural engine cool down, or as cold start after forced cool down and the engine, coolant and oil temperatures, aftertreatment systems and all engine control devices are stabilized between 20 °C and 30 °C. The measurement of the cold start emissions shall be started with the start of the cold engine.

b) Hot soak period – Immediately upon completion of the cold start phase, the engine shall be shut-down and conditioned for the hot start by a 20 min ±1 min hot soak period.

c) The hot-start shall be started immediately after the soak period with the cranking of the engine. The gaseous analysers shall be switched on at least 10 s before the end of the soak period to avoid switching signal peaks. The measurement of emissions shall be started in parallel with the start of the hot start phase including the cranking of the engine.

Brake specific emissions expressed in (g/kWh), or number per kilowatt-hour (#/kWh) for PN, shall be determined by using the procedures of Clause 9 or H.7 for both the cold and hot start NRTC. Composite weighted emissions shall be computed by weighting the cold start results by 10 % and the hot start results by 90 % as detailed in Clause 9 or H.7. Other weighting factors for cold start (e.g. 5 %) and hot start (e.g. 95 %) NRTC can be used if required by the parties involved. Sum of the two-weighting factor must add to 100 %

7.6.3 Large spark-ignition non-road transient cycle

The large spark-ignition non-road transient cycle (LSI-NRTC) may be applied to variable-speed spark-ignition engines for mobile use (NRMM) that are also subject to the C2 steady-state (discrete- or ramped- modal) cycle and conform to characteristics a) or b), and c):

a) a maximum power output between 19 kW and 30 kW with a swept volume ≥1 l;

b) a maximum power output greater than 30 kW but less than 560 kW;

c) a maximum engine speed ≤3 400 rpm.

This cycle does not apply to non-road engines that are not subject to the C2 test cycle and does not apply to engines for non-road utility vehicles with displacement ≤1 l and maximum power ≤30 kW, snowmobiles, off-highway motorcycles or all-terrain vehicles (ATVs).

The sequence of normalized speed and torque values is given in C.3.

7.6.3.1 Test sequence for LSI-NRTC

The transient test cycle shall be run once after completion of pre-conditioning:

a) Warm up the test engine by starting and operating for the first 180 s of the duty cycle, then operate at idle without load for 30 s. Emissions are not measured during this warm-up sequence.

b) At the end of the 30-second idling period start measuring emissions and operate the engine over the entire duty cycle starting from the beginning.

Brake specific emissions expressed in (g/kWh), or number per kilowatt-hour (#/kWh) for PN, shall be determined by using the procedures of Clause 9 or H.7.

If the engine was already operating before the test, use good engineering judgment to let the engine cool down enough so measured emissions will accurately represent those from an engine starting at room temperature. For example, if an engine starting at room temperature warms up enough in 3 min to start closed-loop operation and achieve full catalyst activity, then minimal engine cooling is necessary before starting the next test.

With the agreement of the parties involved, the engine warm-up procedure may include up to 15 min of operation over the duty cycle.

7.7 Test cycle generation

7.7.1 Generation of steady-state discrete-mode or RMC test cycles

This clause shall be used to generate the engine speeds and loads over which the engine shall be operated during steady-state discrete-mode or RMC tests.

7.7.1.1 Generation of test speeds for engines tested with both transient and steady-state cycles

For engines that are tested with a transient cycle in addition to a steady-state cycle the MTS specified in 7.2.1 shall be used as the 100 % speed for both transient and steady state tests. A declared MTS as specified by 7.2.1.2 is permitted at the choice of the manufacturer.

The MTS shall be used in place of rated speed when determining intermediate speed according to 7.2.3.

The idle speed shall be determined according to 7.2.4.

7.7.1.2 Generation of test speeds for engines only tested with steady-state cycles

For engines that are not tested with a transient cycle, the maximum test speed specified in 7.2.2 shall be used as the 100 % speed.

The rated speed shall be used to determine the intermediate speed according to 7.2.3. If the cycle in Annex A or B specifies additional speeds as a percentage they shall be calculated as a percentage of the rated speed.

The idle speed shall be determined according to 7.2.4.

At manufacturers' discretion, MTS may be used to replace rated speed for the generation of test speeds in this clause.

7.7.1.3 Generation of load settings for each test mode

The per cent load for each test mode of the chosen test cycle shall be taken from the appropriate table of Annex A or B. Depending upon the test cycle, the load in these tables is expressed as either power or torque relative to a specified value at the specified engine speed, as listed in 7.3 and in the footnotes for each table.

The 100 % value at a given test speed shall be the measured or declared value taken from the mapping curve generated according to 7.4.2 or 7.4.3 respectively, expressed as power (kW). The engine setting for each test mode shall be calculated using the formula:

$$S=\left(\left(P_{100\%}+P_{\mathrm{AUX}}\right)\times\frac{L}{100}\right)-P_{\mathrm{AUX}} \qquad (12)$$

where

S is dynamometer setting in kW;

$P_{100\%}$ is 100 % value of measured or declared power at the specified test speed in kW;

P_{AUX} is sum of the declared total power absorbed by auxiliaries that are to be removed for the test but which are installed minus the declared total power absorbed by auxiliaries that should be fitted for the test but were not installed, (see 5.2.4) at the specified test speed in kW;

L is % torque.

A warm minimum torque that is representative of in-use operation may be declared. For example, if the engine is typically connected to a machine that does not operate below a certain minimum torque, this torque may be declared and used for any load point that would otherwise fall below this value.

In the case of cycle D1 and D2 the manufacturer shall declare the maximum continuous power and rated power respectively and these shall be used as 100 % power when generating the test cycle.

7.7.2 Generation of NRTC and LSI-NRTC

This clause shall be used to generate the engine speeds and loads over which the engine shall be operated during NRTC or LSI-NRTC tests.

7.7.2.1 Denormalization of engine speed

Each engine speed from Annex C shall be denormalized using the following formula:

$$n_{ref} = \frac{n_{norm} \times (n_{MTS} - n_{idle})}{100} + n_{idle} \tag{13}$$

where

n_{ref}	is reference speed;
n_{MTS}	is maximum test speed;
n_{idle}	is idle speed;
n_{norm}	is value of NRTC or LSI-NRTC normalized speed taken from Annex C.

A declared MTS as specified by 7.2.1.2 is permitted at the choice of the manufacturer.

7.7.2.2 Denormalization of engine torque

The torque values in the engine dynamometer schedule of Annex C are normalized to the maximum torque at the respective speed. The torque values of the reference cycle shall be denormalized, using the mapping curve determined according to 7.4.1, as follows:

$$T_{ref} = \frac{T_{norm} \times T_{max}}{100} \tag{14}$$

where

T_{ref}	is reference torque for the respective reference speed;
T_{max}	is maximum torque for the respective test speed taken from the engine mapping performed according to 7.4.1 adjusted where necessary according to 7.7.2.2.1;
T_{norm}	is value of NRTC or LSI-NRTC normalized torque taken from Annex C.

7.7.2.2.1 Adjustment of engine torque due to auxiliaries fitted for the emissions test

Where auxiliaries are fitted in accordance with Annex G there shall be no adjustment to the maximum torque for the respective test speed taken from the engine mapping performed according to 7.4.1.

Where, according to 5.2.1 or 5.2.2 necessary auxiliaries that should have been fitted for the test are not installed, or auxiliaries that should have been removed for the test are installed, the value of T_{max} shall be adjusted according to this clause.

$$T_{max} = T_{map} - T_{AUX} \tag{15}$$

where

T_{map} is unadjusted maximum torque for the respective test speed taken from the engine mapping performed according to 7.4.1;

T_{AUX} $= T_r - T_f$;

T_f is torque required to drive auxiliaries that should have been fitted but were not installed for the test;

T_r is torque required to drive auxiliaries that should have been removed for the test but were installed for the test.

7.7.2.2.2 Declared minimum torque

A minimum torque that is representative of in-use operation may be declared. For example, if the engine is typically connected to a machine that does not operate below a certain minimum torque, this torque may be declared and used for any load point that would otherwise fall below this value.

7.7.2.3 Example of denormalization procedure

As an example, the following test point shall be denormalized:

n_{norm} = 43 %

T_{norm} = 82 %

Given the following values:

n_{MTS} = 2 200 /min

n_{idle} = 600 /min

The actual speed can be calculated as follows:

$$n_{act} = \frac{43(2\,200 - 600)}{100} + 600 = 1\,288\,/\,\text{min}$$

With the maximum torque of 700 Nm observed from the mapping curve at 1 288 /min, the actual torque is:

$$T_{act} = \frac{82 \times 700}{100} = 574\ \text{Nm}$$

8 Test run

8.1 General test sequence

To measure engine emissions the following steps have to be performed:

a) The engine test speeds and test loads have to be defined for the engine to be tested by measuring the max torque (for constant-speed engines) or max torque curve (for variable-speed engines) as function of the engine speed.

b) Normalized test cycles have to be denormalized with the torque (for constant-speed engines) or speeds and torques (for variable-speed engines) found in 8.1 a).

c) The engine, equipment, and measurement instruments shall be prepared for the following emission test or test series (cold and hot cycle) in advance.

d) Pre-test procedures shall be performed to verify proper operation of certain equipment and analysers. All analysers have to be calibrated. All pre-test data shall be recorded.

e) The engine shall be started (NRTC) or kept running (LSI-NRTC and steady-state cycles) at the beginning of the test cycle and the sampling systems shall be started at the same time.

f) Emissions and other required parameters shall be measured or recorded during sampling time (for NRTC and ramped-modal steady-state cycles throughout the whole test cycle.

g) Post-test procedures shall be performed to verify proper operation of certain equipment and analysers.

h) PM filter(s) shall be pre-conditioned, weighed (empty weight), loaded, re-conditioned, again weighed (loaded weight) and then samples shall be evaluated according to pre- (8.4.1) and post-test (8.7.2) procedures.

i) Emission test results shall be evaluated.

The following diagram gives an overview about the procedures needed to conduct NRMM test cycles with measuring exhaust engine emissions.

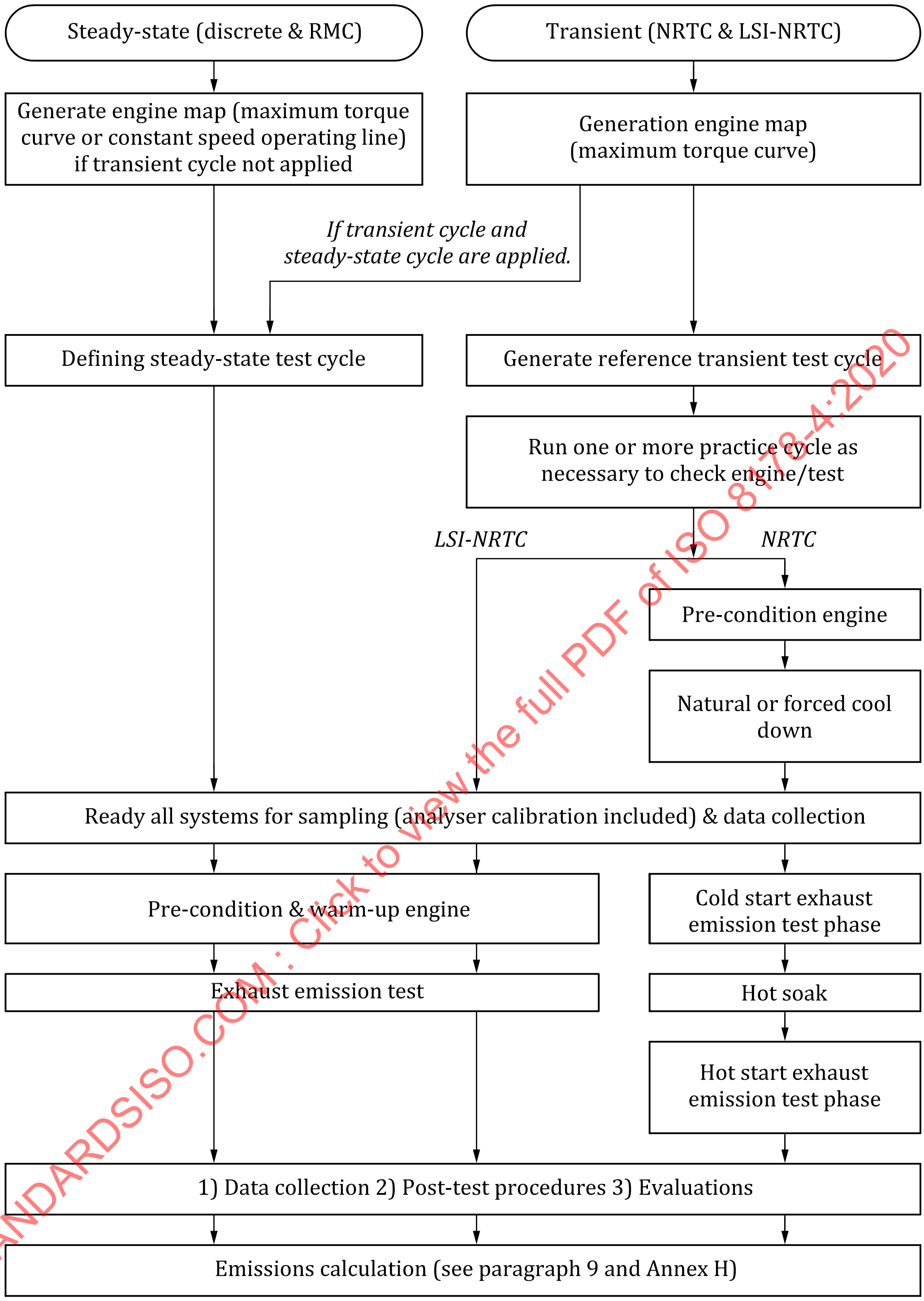


Figure 5 — Test sequence

8.2 Instrument validation for test

8.2.1 Validation of proportional flow control for batch sampling and minimum dilution ratio for PM batch sampling

8.2.1.1 Proportionality criteria for CVS

8.2.1.1.1 Proportional Sample Flow Rate (Example: Raw PFS Application)

For any pair of flow meters, the recorded sample and total flow rates or their 1 Hz means shall be used with the statistical calculations in ISO 8178-1:2020, D.10. The standard error of the estimate, S_{EE}, of the sample flow rate versus the total flow rate shall be determined. For each test interval, it shall be demonstrated that S_{EE} was less than or equal to 3,5 % of the mean sample flow rate.

8.2.1.1.2 Constant Sample Flow Rate (Example: CVS Secondary Dilution System Applicaton)

For any pair of flow meters, the recorded sample and total flow rates or their 1 Hz means shall be used to demonstrate that each flow rate was constant within ±2,5 % of its respective mean or target flow rate. The following options may be used instead of recording the respective flow rate of each type of meter:

a) Critical-flow venturi option. For critical-flow venturis, the recorded venturi-inlet conditions or their 1 Hz means shall be used. It shall be demonstrated that the flow density at the venturi inlet was constant within ±2,5 % of the mean or target density over each test interval. For a CVS critical-flow venturi, this may be demonstrated by showing that the absolute temperature at the venturi inlet was constant within ±4 % of the mean or target absolute temperature over each test interval.

b) Positive-displacement pump option. The recorded pump-inlet conditions or their 1 Hz means shall be used. It shall be demonstrated that the flow density at the pump inlet was constant within ±2,5 % of the mean or target density over each test interval. For a CVS pump, this may be demonstrated by showing that the absolute temperature at the pump inlet was constant within ±2 % of the mean or target absolute temperature over each test interval.

8.2.1.1.3 Demonstration of proportional sampling

For any proportional batch sample such as a bag or PM filter, it shall be demonstrated that proportional sampling was maintained using one of the following, noting that up to 5 % of the total number of data points may be omitted as outliers.

Using good engineering judgement, it shall be demonstrated with an engineering analysis that the proportional-flow control system inherently ensures proportional sampling under all circumstances expected during testing. For example, CFVs may be used for both sample flow and total flow if it is demonstrated that they always have the same inlet pressures and temperatures and that they always operate under critical-flow conditions.

Measured or calculated flows and/or tracer gas concentrations (e.g. CO_2) shall be used to determine the minimum dilution ratio for PM batch sampling over the test interval.

8.2.1.2 Partial flow dilution system validation

For the control of a partial flow dilution system to extract a proportional raw exhaust gas sample, a fast system response is required; this is identified by the promptness of the partial flow dilution system. The transformation time for the system shall be determined by the procedure in ISO 8178-1:2020, 9.8.6.3.2 and the related Figure 1. The actual control of the partial flow dilution system shall be based on the current measured conditions. If the combined transformation time of the exhaust gas flow measurement and the partial flow system is ≤0,3 s, online control shall be used. If the transformation time exceeds 0,3 s, look-ahead control based on a pre-recorded test run shall be used. In this case, the combined rise time shall be ≤1 s and the combined delay time ≤10 s.The total system response shall be designed so as to ensure a representative sample of the particulates, $q_{mp,i}$, proportional to the exhaust mass flow. To determine the proportionality, a regression analysis of $q_{mp,i}$ versus $q_{mew,i}$ shall be conducted on a minimum 5 Hz data acquisition rate, and the following criteria shall be met:

a) The correlation coefficient r^2 of the linear regression between $q_{mp,i}$ and $q_{mew,i}$ shall not be less than 0,95.

b) The standard error of estimate of $q_{mp,i}$ on $q_{mew,i}$ shall not exceed 5 % of q_{mp} maximum.

c) q_{mp} intercept of the regression line shall not exceed ±2 % of q_{mp} maximum.

Look-ahead control is required if the combined transformation times of the particulate system, $t_{50,\mathrm{P}}$ and of the exhaust gas mass flow signal, $t_{50,\mathrm{F}}$ are >0,3 s. In this case, a pre-test shall be run and the exhaust gas mass flow signal of the pre-test be used for controlling the sample flow into the particulate system. A correct control of the partial dilution system is obtained, if the time trace of $q_{mew,pre}$ of the pretest, which controls q_{mp}, is shifted by a “look-ahead” time of $t_{50,\mathrm{P}} + t_{50,\mathrm{F}}$.

For establishing the correlation between $q_{mp,i}$ and $q_{mew,i}$ the data taken during the actual test shall be used, with $q_{mew,i}$ time aligned by $t_{50,\mathrm{F}}$ relative to $q_{mp,i}$ (no contribution from $t_{50,\mathrm{P}}$ to the time alignment). That is, the time shift between q_{mew} and q_{mp} is the difference in their transformation times that were determined in ISO 8178-1:2020, 9.8.6.3.2.

8.2.2 Gas analyser range validation, drift validation and drift correction

8.2.2.1 Range validation

If an analyser operated above 100 % of its range at any time during the test, the following steps shall be performed:

8.2.2.1.1 Batch sampling

For batch sampling, the sample shall be re-analysed using the lowest analyser range that results in a maximum instrument response below 100 %. The result shall be reported from the lowest range from which the analyser operates below 100 % of its range for the entire test.

8.2.2.1.2 Continuous sampling

For continuous sampling, the entire test shall be repeated using the next higher analyser range. If the analyser again operates above 100 % of its range, the test shall be repeated using the next higher range. The test shall be continued to be repeated until the analyser always operates at less than 100 % of its range for the entire test.

8.2.2.2 Drift validation and drift correction

If the drift is within ±1 %, the data can be either accepted without any correction or accepted after correction. If the drift is greater than ±1 %, two sets of brake specific emission results shall be calculated for each pollutant with a brake-specific limit value and for CO_2, or the test shall be voided. One set shall be calculated using data before drift correction and another set of data calculated after correcting all the data for drift according to Clause 9 or Annex H. The comparison shall be made as a percentage of the uncorrected results. The difference between the uncorrected and the corrected brake-specific emission values shall be within ±4 % of the uncorrected brake-specific emission values, or the emission limit value, if applicable, whichever is greater. If not, the entire test is void.

8.2.3 PM sampling media (e.g. filters) preconditioning and tare weighing

Before an emission test, the following steps shall be taken to prepare PM sample filter media and equipment for PM measurements:

8.2.3.1 Periodic verifications

It shall be made sure that the balance and PM-stabilization environments meet the periodic verifications in ISO 8178-1:2020, 9.6.3. The reference filter shall be weighed just before weighing test filters to establish an appropriate reference point (see details of the procedure in ISO 8178-1:2020, 9.6.3). The reference filters are used to indicate whether or not the conditions at the time of test filter stabilisation may have caused contamination of test filters, subsequent to the pre-test mass determination of the filter. The verification of the stability of the reference filters shall occur after the post-test stabilisation period, immediately before the post-test weighing.

8.2.3.2 Visual inspection

The unused sample filter media shall be visually inspected for defects, defective filters shall be discarded.

8.2.3.3 Grounding

Electrically grounded tweezers or a grounding strap shall be used to handle PM filters as described in ISO 8178-1:2020, 8.1.5.3.

8.2.3.4 Unused sample media

Unused sample media shall be placed in one or more containers that are open to the PM-stabilization environment. If filters are used, they may be placed in the bottom half of a filter cassette.

8.2.3.5 Stabilization

Sample media shall be stabilized in the PM-stabilization environment. An unused sample medium can be considered stabilized as long as it has been in the PM-stabilization environment for a minimum of 30 min, during which the PM-stabilization environment has been within the specifications of ISO 8178-1:2020, 8.1.5. However, if a mass of 400 µg or more is expected, then the sample media shall be stabilised for at least 60 min.

8.2.3.6 Weighing

The sample media shall be weighed automatically or manually, as follows:

a) For automatic weighing, the automation system manufacturer's instructions shall be followed to prepare samples for weighing. This may include placing the samples in a special container.

b) For manual weighing, good engineering judgement shall be used.

c) Optionally, substitution weighing is permitted (see 8.2.3.10).

d) Once a filter is weighed it shall be returned to the Petri dish and covered.

8.2.3.7 Buoyancy correction

The measured weight shall be corrected for buoyancy as described in ISO 8178-1:2020, 9.6.3.5.

8.2.3.8 Repetition

The filter mass measurements may be repeated to determine the average mass of the filter using good engineering judgement and to exclude outliers from the calculation of the average.

8.2.3.9 Tare-weighing

Unused filters that have been tare-weighed shall be loaded into clean filter cassettes and the loaded cassettes shall be placed in a covered or sealed container before they are taken to the test cell for sampling. The filter cassettes should be kept clean by periodically washing or wiping them with a compatible solvent applied using a lint-free cloth. Depending upon the cassette material, ethanol (C_2H_5OH) might be an acceptable solvent. The cleaning frequency will depend on the engine's level of PM and HC emissions.

8.2.3.10 Substitution weighing

Substitution weighing is an option and, if used, involves measurement of a reference weight before and after each weighing of a PM sampling medium (e.g. filter). While substitution weighing requires more measurements, it corrects for a balance's zero-drift and it relies on balance linearity only over a small range. This is most appropriate when quantifying total PM masses that are less than 0,1 % of the sample medium's mass. However, it may not be appropriate when total PM masses exceed 1 % of the sample medium's mass. If substitution weighing is used, it shall be used for both pre-test and post-test weighing. The same substitution weight shall be used for both pre-test and post-test weighing. The mass of the substitution weight shall be corrected for buoyancy if the density of the substitution weight is less than 2,0 g/cm^3. The following steps are an example of substitution weighing:

a) Electrically grounded tweezers or a grounding strap shall be used, as described in ISO 8178-1:2020, 8.1.5.3.

b) A static neutralizer shall be used as described in ISO 8178-1:2020, 8.1.5.3 to minimize static electric charge on any object before it is placed on the balance pan.

c) A substitution weight shall be selected that meets the specifications for calibration weights in ISO 8178-1:2020, 8.1.5.2. The substitution weight shall also have the same density as the weight that is used to span the microbalance, and shall be similar in mass to an unused sample medium (e.g. filter). If filters are used, the weight's mass should be about (80 to 100) mg for typical 47 mm diameter filters.

d) The stable balance reading shall be recorded and then the calibration weight shall be removed.

e) An unused sampling medium (e.g. a new filter) shall be weighed, the stable balance reading recorded and the balance environment's dew point, ambient temperature, and atmospheric pressure recorded.

f) The calibration weight shall be reweighed and the stable balance reading recorded.

g) The arithmetic mean of the two calibration-weight readings that were recorded immediately before and after weighing the unused sample shall be calculated. That mean value shall be subtracted from the unused sample reading, then the true mass of the calibration weight as stated on the calibration-weight certificate shall be added. This result shall be recorded. This is the unused sample's tare weight without correcting for buoyancy.

h) These substitution-weighing steps shall be repeated for the remainder of the unused sample media.

i) The instructions given in 8.2.3.7 to 8.2.3.9 shall be followed once weighing is completed.

8.3 Sample system decontamination and preconditioning

Good engineering judgment shall be used to determine if the sampling system needs to be decontaminated and preconditioned.

Contamination occurs when a pollutant accumulates in the sample system in a high enough concentration to cause release during emission tests. A sampling system is considered decontaminated if the contaminants are in equilibrium with measured exhaust emissions. Note that although this clause focuses on avoiding excessive contamination of sample systems, good engineering judgment should also be used to avoid loss of sample to a sample system that is too clean. The goal of decontamination is not to perfectly clean the sample system, but rather to achieve equilibrium between the sample system and the exhaust so emission components are neither lost to nor entrained from the sample system.

a) The contamination checks may be performed as follows to determine if decontamination is needed:

   1) For dilute exhaust sampling systems, hydrocarbon and PM emissions shall be measured by sampling with the CVS dilution air turned on, without an engine connected to it.

   2) For raw analysers and systems that collect PM samples from raw exhaust, hydrocarbon and PM emissions shall be measured by sampling purified air or nitrogen.

   3) When calculating zero emission levels, all applicable corrections shall be applied, including initial THC contamination and diluted (CVS) exhaust background corrections.

   4) Sampling systems are considered contaminated if either of the following conditions applies:

      i) The hydrocarbon emission level exceeds 2 % of the flow-weighted mean wet, net concentration expected at the HC standard.

      ii) The PM emission level exceeds 5 % of the level expected at the standard and exceeds 20 µg on a 47 mm PTFE membrane filter.

b) To precondition/decontaminate sampling systems, the following procedure should be used or good engineering judgment shall be used to select a different procedure:

   1) The engine shall be started and good engineering judgment shall be used to operate it at a condition that generates high exhaust temperatures at the sample probe inlet.

   2) Any dilution systems shall be operated at their expected flow rates. Aqueous condensation shall be prevented in the dilution systems.

   3) Any PM sampling systems shall be operated at their expected flow rates.

   4) PM shall be sampled for at least 10 min using any sample media. The sample media may be changed at any time during this process and may be discarded without weighing them.

   5) Any gaseous sampling systems that do not require decontamination during this procedure may be purged.

   6) Calibrations or verifications on any idle equipment or analysers may be conducted during this procedure.

c) If the sampling system is still contaminated following the procedures specified in b) of this clause, more aggressive procedures may be used to decontaminate the sampling system, as long as the decontamination does not cause the sampling system to be cleaner than an equilibrium condition such that artificially low emission measurements may result.

8.3.1 Verification of HC contamination

If there is any presumption of an essential HC contamination of the exhaust gas measuring system, the contamination with HC may be checked with zero gas and the hang-up may then be corrected. If the amount of contamination of the measuring system and the background HC system has to be checked, it shall be conducted within 8 hours of starting each test-cycle. The values shall be recorded for later correction. Before this check, the leak check has to be performed and the FID analyser has to be calibrated.

If any of the initial THC concentration values exceed the greatest of the following values, the source of the contamination shall be determined and corrective action shall be taken, such as purging the system during an additional preconditioning cycle or replacing contaminated portions:

a) 2 % of the flow-weighted mean concentration expected at the HC (THC or NMHC) standard;

b) 2 % of the flow-weighted mean concentration of HC (THC or NMHC) measured during testing;

c) 2 µmol/mol.

8.4 Pre-test procedures

8.4.1 Preparation of the sampling filters

At least one hour before the test, each filter shall be placed in a Petri dish, which is protected against dust contamination and allows air exchange, and placed in a weighing chamber for stabilization. At the end of the stabilization period, each filter shall be weighed and the tare weight shall be recorded. The filter shall then be stored in a closed Petri dish or sealed filter holder until needed for testing. The filter shall be used within eight hours of its removal from the weighing chamber.

8.4.2 General requirements for preconditioning the sampling system and the engine

To achieve stable conditions, the sampling system and the engine shall be preconditioned before starting a test sequence as specified in this clause.

The intent of preconditioning is to manage the representativeness of emissions and emission controls over the duty cycle and to reduce bias in order to meet stable conditions for the following emission test.

Emissions may be measured during preconditioning cycles as long as a predefined number of preconditioning cycles are performed and the measurement system has been started according to the requirements of 8.4.4.

The amount of preconditioning shall be identified by the engine manufacturer before starting to precondition. Preconditioning shall be performed as follows, noting that the specific cycles for preconditioning are the same ones that apply for emission testing.

8.4.2.1 Cold-start transient cycle (NRTC)

The engine shall be preconditioned by running at least one hot-start transient cycle. Additional cycles shall be permitted. Immediately after completing each preconditioning cycle, the engine shall be shut down and the engine-off hot-soak period shall be completed. Immediately after completing the last preconditioning cycle, the engine shall be shut down and the engine cool down described in 8.4.3 shall be started.

8.4.2.2 Hot-start transient cycle (hot-start NRTC or LSI-NRTC)

This clause describes the pre-conditioning that shall be applied when it is intended to sample emissions from the hot-start NRTC without running the cold start NRTC, or for the LSI-NRTC. The engine shall be preconditioned by running at least one hot-start transient cycle. Immediately after completing each preconditioning cycle, the engine shall be shut down, and then the next cycle shall be started as soon as practical. The next preconditioning cycle should be started within 60 s after completing the last preconditioning cycle. Where applicable, following the last pre-conditioning cycle the appropriate hot-soak (hot-start NRTC) or cool-down (LSI-NRTC) period shall apply before the engine is started for the emissions test. Where no hot-soak or cool-down period applies the emissions test should be started within 60 s after completing the last pre-conditioning cycle.

8.4.2.3 Discrete-mode cycle for steady-state testing

The engine shall be warmed up according to the recommendation of the manufacturer and good engineering judgment. Before emission sampling can start, the engine shall be running either:

a) on mode 1 of the appropriate test cycle until engine temperatures (cooling water and lube oil) have been stabilized (normally at least 10 min and no less than 5 min); or

b) until engine temperatures (cooling water and lube oil) have been stabilized on 50 % speed and 50 % torque for any discrete-mode NRSC test cycle other than type D2, E2, or G, or nominal engine speed and 50 % torque for any discrete-mode NRSC test cycle D2, E2 or G. The 50 % speed is calculated in accordance with 7.7.2.1 in the case of an engine, where MTS is used for the generation of test speeds, and calculated in accordance with 7.7.1.2 in all other cases. 50 % torque is defined as 50 % of the maximum available torque at this speed.

The emissions test shall be started without stopping the engine.

8.4.2.4 Ramped-modal cycle for steady-state testing

The engine manufacturer shall select one of the following pre-conditioning sequences a) or b). The engine shall be pre-conditioned according to the chosen sequence.

a) The engine shall be preconditioned by running at least the second half of the ramped-modal cycle, based on the number of test modes. Additional cycles shall be permitted. The engine shall not be shut down between cycles. Immediately after completing each preconditioning cycle, the next cycle (including the emission test) shall be started as soon as practical. Where possible, the next cycle should be started within 60 s after completing the last preconditioning cycle.

b) The engine shall be warmed-up and run until engine temperatures (cooling water and lube oil) have been stabilized on 50 % speed and 50 % torque for any RMC test cycle other than type D, E2, or G, or nominal engine speed and 50 % torque for any RMC test cycle D, E2 or G. The 50 % speed is calculated in accordance with 7.7.2.1 in the case of an engine where MTS is used for the generation of test speeds, and calculated in accordance with 7.7.1.2 in all other cases. 50 % torque is defined as 50 % of the maximum available torque at this speed.

8.4.3 Engine cool down (NRTC)

A natural or forced cool-down procedure may be applied.

Good engineering judgment shall be used to set up systems to send cooling air across the engine, to send cool oil through the engine lubrication system, to remove heat from coolant through the engine cooling system, and to remove heat from any exhaust aftertreatment systems. In the case of a forced aftertreatment cool-down, good engineering judgment would indicate that the flowing of cooling air shall not be started until the aftertreatment system has cooled below its catalytic activation temperature. For platinum-group metal catalysts, this temperature is about 200 °C. Once the aftertreatment system has naturally cooled below its catalytic activation temperature, good engineering judgment would indicate that clean air with a temperature of at least 15 °C shall be used, and the air directed through the aftertreatment system in the normal direction of exhaust flow.

Any cooling procedure that results in unrepresentative emissions is not permitted.

8.4.4 Preparation of measurement equipment for sampling

The following steps shall be taken before emission sampling begins:

a) Leak checks shall be performed within 8 hours prior to emission sampling according to ISO 8178-1:2020, 9.3.

b) For batch sampling, clean storage media shall be connected, such as evacuated bags or tare-weighed filters.

c) All measurement instruments shall be started according to the instrument manufacturer's instructions and good engineering judgment.

d) Dilution systems, sample pumps, cooling fans, and the data-collection system shall be started.

e) The sample flow rates shall be adjusted to desired levels, using bypass flow, if desired.

f) Heat exchangers in the sampling system shall be pre-heated or pre-cooled to within their operating temperature ranges for a test.

g) Heated or cooled components such as sample lines, filters, chillers, and pumps shall be allowed to stabilize at their operating temperatures.

h) Exhaust dilution system flow shall be switched on at least 10 min before a test sequence.

i) Calibration of gas analysers and zeroing of continuous analysers shall be carried out according to the procedure of 8.4.5.

j) Any electronic integrating devices shall be zeroed or re-zeroed, before the start of any test interval.

8.4.5 Calibration of gas analysers

Appropriate gas analyser ranges shall be selected. Emission analysers with automatic or manual range switching are allowed. During a ramped-modal or a NRTC test and during a sampling period of a gaseous emission at the end of each mode for discrete mode testing, the range of the emission analysers may not be switched. Also the gains of an analyser's analogue operational amplifier(s) may not be switched during a test cycle.

All continuous analysers shall be zeroed and spanned using gases that meet the specifications of ISO 8178-1:2020, 9.2. FID analysers shall be spanned on a carbon number basis of one (C_1).

If sample bags are used, they shall be evacuated.

8.4.6 Adjustment of the dilution system

The total diluted exhaust gas flow of a full flow dilution system or the diluted exhaust gas flow through a partial flow dilution system shall be set to eliminate water condensation in the system, and to obtain a filter face temperature between 42 °C and 52 °C.

8.5 Engine starting and restarting

8.5.1 Engine start

The engine shall be started:

a) as recommended in the owner's manual using a production starter motor or air-start system and either an adequately charged battery, a suitable power supply or a suitable compressed air source; or

b) by using the dynamometer to crank the engine until it starts. Typically motor the engine within ±25 % of its typical in-use cranking speed or start the engine by linearly increasing the dynamometer speed from zero to 100 min^{-1} below low idle speed but only until the engine starts.

Cranking shall be stopped within 1 s of starting the engine. If the engine does not start after 15 s of cranking, cranking shall be stopped and the reason for the failure to start determined, unless the owner's manual or the service-repair manual describes a longer cranking time as normal.

8.5.2 Engine stalling

a) If the engine stalls anywhere during the cold start test of the NRTC, the test shall be voided.

b) If the engine stalls anywhere during the hot start test of the NRTC, the test shall be voided. The engine shall be soaked according to 7.6.2.1, and the hot start test repeated. In this case, the cold start test does not need to be repeated.

c) If the engine stalls anywhere during the LSI-NRTC, the test shall be voided. The engine shall be preconditioned and the test be repeated.

d) If the engine stalls anywhere during the test, it shall be voided and be repeated beginning with the engine warm-up procedure. In the case of PM measurement utilizing the multi-filter method (one sampling filter for each operating mode), the test shall be continued by stabilizing the engine at the previous mode or at the mode where the cycle was interrupted for engine temperature conditioning and then initiating measurement with the mode where the engine stalled.

8.6 Test cycle running procedure

8.6.1 Test sequence for discrete steady-state test cycles

8.6.1.1 Engine warm up

The engine shall be warmed-up using the pre-conditioning sequence in 8.4.2.3. Immediately from this engine conditioning point, the test cycle measurement starts without stopping the engine.

8.6.1.2 Performing discrete-mode test cycles

The test shall be performed in ascending order of mode numbers as set out for the test cycle (see Annex A).

Each mode has a mode length of at least 10 min, except when testing spark-ignition engines using cycles G1, G2 or G3 where each mode has a length of at least 3 min. In each mode the engine shall be stabilized for at least 5 min and emissions shall be sampled for 1 min to 3 min for gaseous and where applicable, PN emissions at the end of each mode, except when testing spark-ignition engines using cycles G1, G2 or G3 where emissions shall be sampled for at least the last 2 min of the respective test mode. Extended time of sampling is permitted to improve the accuracy of PM sampling.

The mode length shall be recorded and reported.

The PM sampling may be done either with the single filter method or with the multiple filter method. Since the results of the methods may differ slightly, the method used shall be declared with the results;

For the single filter method, the modal weighting factors specified in the test cycle procedure and the actual exhaust flow shall be taken into account during sampling by adjusting sample flow rate and/or sampling time, accordingly. It is required that the effective weighting factor (according to 9.2.5) of the PM sampling is within ±0,005 of the weighting factor of the given mode as given in Annex A.

Sampling shall be conducted as late as possible within each mode. For the single filter method, the completion of PM sampling shall be coincident within ±5 s with the completion of the gaseous emission measurement. The sampling time per mode shall be at least 20 s for the single filter method and at least 60 s for the multi-filter method. For systems without bypass capability, the sampling time per mode shall be at least 60 s for single and multiple filter methods.

The engine speed and load, intake air temperature, fuel flow and where applicable air or exhaust gas flow shall be measured for each mode at the same time interval which is used for the measurement of the gaseous concentrations; any additional data required for calculation shall be recorded.

If the engine stalls or the emission sampling is interrupted at any time after emission sampling begins for a discrete mode and the single filter method, the test shall be voided and be repeated beginning with the engine warm-up procedure. In the case of PM measurement utilizing the multi-filter method (one sampling filter for each operating mode) utilizing the multi-filter method, the test shall be continued by stabilizing the engine at the previous mode for engine temperature conditioning and then initiating measurement with the mode where the engine stalled.

Post-test procedures according to 8.7 shall be performed.

8.6.1.3 Validation criteria

During each mode of the given steady-state test cycle after the initial transition period, the measured speed shall not deviate from the reference speed for more than ±1 % of rated speed or ±3 min^{-1}, whichever is greater except for idle which shall be within the tolerances declared by the manufacturer. The measured torque shall not deviate from the reference torque for more than ±2 % of the maximum torque at the test speed.

8.6.2 Ramped-modal test cycles

8.6.2.1 Engine warming-up

The engine shall be warmed-up using the pre-conditioning sequence in 8.4.2.4. Immediately after the engine conditioning procedure, engine speed and torque shall be changed in a linear ramp of 20 s ± 1 s to the first mode of the test. Within 10 s after the end of the ramp, the test cycle measurement shall start.

8.6.2.2 Performing a ramped-modal test cycle

The ramped-modal cycles are shown in Annex B.

The engine shall be operated for the prescribed time in each mode. The transition from one mode to the next shall be done linearly in 20 s ± 1 s following the tolerances prescribed in 8.6.2.4. (see Annex B).

For ramped-modal cycles, reference speed and torque values shall be generated at a minimum frequency of 1 Hz and this sequence of points shall be used to run the cycle. During the transition between modes, the denormalized reference speed and torque values shall be linearly ramped between modes to generate reference points. The normalized reference torque values shall not be linearly ramped between modes and then denormalized. If the speed and torque ramp runs through a point above the engine's torque curve, it shall continue to command the reference torques and it shall be allowed for the operator demand to go to maximum.

Over the whole RMC test cycle (during each mode and including the ramps between the modes), the concentration of each gaseous pollutant shall be measured and the PM and where applicable, PN be sampled. The gaseous pollutants may be measured raw or diluted and be recorded continuously; if diluted, they can also be sampled into a sampling bag. The particulate sample shall be diluted with conditioned and clean air. One sample over the complete test procedure shall be taken, and in case of PM collected on a single sampling filter.

For calculation of the brake specific emissions, the actual cycle work shall be calculated by integrating actual engine power over the complete cycle.

8.6.2.3 Emission test sequence

a) Execution of the RMC, sampling exhaust gases, recording data, and integrating measured values shall be started simultaneously.

b) Speed and torque shall be controlled to the first mode in the test cycle.

c) If the engine stalls anywhere during the RMC execution, the test shall be voided. The engine shall be pre-conditioned and the test repeated.

d) At the end of the RMC, sampling shall be continued, except for PM sampling, operating all systems to allow system response time to elapse. Then all sampling and recording shall be stopped, including the recording of background samples. Finally, any integrating devices shall be stopped and the end of the test cycle shall be indicated in the recorded data.

e) Post-test procedures according to 8.7 shall be performed.

8.6.2.4 Validation criteria

RMC tests shall be validated using the regression analysis as described in 8.6.3.4 and 8.6.3.6. The allowed RMC tolerances are given in Table 3. Note that the RMC tolerances are different from the NRTC tolerances of Table 4. When conducting testing of engines of maximum power greater than 560 kW, the regression line tolerances of Table 4 and the point deletion of Table 5 may be used.

Table 3 — RMC regression line tolerances

	Speed	Torque	Power
Standard error of estimate (S_{EE}) of y on x	maximum 1 % of rated speed	maximum 2 % of maximum engine torque	maximum 2 % of maximum engine power
Slope of the regression line, a_1	0,99 to 1,01	0,98 to 1,02	0,98 to 1,02
Coefficient of determination, r^2	minimum 0,990	minimum 0,950	minimum 0,950
y intercept of the regression line, a_0	±1 % of rated speed	±20 Nm or 2 % of maximum torque whichever is greater	±4 kW or 2 % of maximum power whichever is greater

In case of running the RMC test not on a transient test bed, where the second by second speed and torque values are not available, the following validation criteria shall be used.

At each mode the requirements for the speed and torque tolerances are given in 8.6.1.3. For the 20 s linear speed and linear torque transitions between the RMC steady-state test modes (7.5.2) the following tolerances for speed and load shall be applied for the ramp, the speed shall be held linear within ±2 % of rated speed. The torque shall be held linear within ±5 % of the maximum torque at rated speed.

8.6.3 Transient test cycle (NRTC and LSI-NRTC)

8.6.3.1 General requirements

Reference speeds and torques commands shall be sequentially executed to perform the transient test cycle. Speed and torque commands shall be issued at a frequency of at least 5 Hz. Because the reference test cycle is specified at 1 Hz, the in between speed and torque commands shall be linearly interpolated from the reference torque values generated from cycle generation.

Small denormalized speed values near warm idle speed may cause low-speed idle governors to activate and the engine torque to exceed the reference torque even though the operator demand is at a minimum. In such cases, it is recommended to control the dynamometer so it gives priority to follow the reference torque instead of the reference speed and let the engine govern the speed.

Under cold-start conditions engines may use an enhanced-idle device to quickly warm up the engine and aftertreatment devices. Under these conditions, very low normalized speeds will generate reference speeds below this higher enhanced idle speed. In this case it is recommended controlling the dynamometer so it gives priority to follow the reference torque and let the engine govern the speed when the operator demand is at minimum.

During an emission test, reference speeds and torques and the feedback speeds and torques shall be recorded with a minimum frequency of 1 Hz, but preferably of 5 Hz or even 10 Hz. This larger recording frequency is important as it helps to minimize the biasing effect of the time lag between the reference and the measured feedback speed and torque values.

The reference and feedback speeds and torques maybe recorded at lower frequencies (as low as 1 Hz), if the average values over the time interval between recorded values are recorded. The average values shall be calculated based on feedback values updated at a frequency of at least 5 Hz. These recorded values shall be used to calculate cycle-validation statistics and total work.

8.6.3.2 Performing an NRTC transient cycle test

Testing shall be started as follows:

The test sequence shall commence immediately after the engine has started from cooled down condition specified in 8.4.3 in case of the cold NRTC test or from hot soak condition in case of the hot NRTC test. The sequence specified in 7.6.2.1 shall be followed.

Data logging, sampling of exhaust gases and integrating measured values shall be initiated simultaneously at the start of the engine. The test cycle shall be initiated when the engine starts and shall be executed according to the schedule of C.2.

At the end of the cycle, sampling shall be continued, operating all systems to allow system response time to elapse. Then all sampling and recording shall be stopped, including the recording of background samples. Finally, any integrating devices shall be stopped and the end of the test cycle shall be indicated in the recorded data.

Post-test procedures according to 8.7 have to be performed.

8.6.3.3 Performing an LSI-NRTC transient cycle test

Testing shall be started as follows:

The test shall commence according to the sequence given in 7.6.3.1.

Data logging, sampling of exhaust gases and integrating measured values shall be initiated simultaneously with the start of the test cycle at the end of the 30-second idle period specified in 7.6.3.1 b). The test cycle shall be executed according to the schedule of C.3.

At the end of the cycle, sampling shall be continued, operating all systems to allow system response time to elapse. Then all sampling and recording shall be stopped, including the recording of background samples. Finally, any integrating devices shall be stopped and the end of the test cycle shall be indicated in the recorded data.

Post-test procedures according to 8.7 shall be performed.

8.6.3.4 Cycle validation criteria for transient test cycle

In order to check the validity of a test, the cycle-validation criteria in this clause shall be applied to the reference and feedback values of speed, torque, power and overall work.

8.6.3.5 Calculation of cycle work

Before calculating the cycle work, any speed and torque values recorded during engine starting shall be omitted. Points with negative torque values have to be accounted for as zero work. The actual cycle work W_{act} (kWh) shall be calculated based on engine feedback speed and torque values. The reference cycle work W_{ref} (kWh) shall be calculated based on engine reference speed and torque values. The actual cycle work W_{act} is used for comparison to the reference cycle work W_{ref} and for calculating the brake specific emissions (see Clause 9).

W_{act} shall be between 85 % and 105 % of W_{ref}.

8.6.3.6 Validation statistics

Linear regression between the reference and the feedback values shall be calculated for speed, torque and power.

To minimize the biasing effect of the time lag between the reference and feedback cycle values, the entire engine speed and torque feedback signal sequence may be advanced or delayed in time with respect to the reference speed and torque sequence. If the feedback signals are shifted, both speed and torque shall be shifted by the same amount in the same direction.

The method of least squares shall be used, with the best-fit formula having the form:

$$y=a_1x+a_0 \tag{16}$$

where

y is feedback value of speed (min^{-1}), torque (Nm), or power (kW);

a_1 is slope of the regression line;

x is reference value of speed (min^{-1}), torque (Nm), or power (kW);

a_0 is y intercept of the regression line.

The standard error of estimate (S_{EE}) of y on x and the coefficient of determination (r^2) shall be calculated for each regression line (ISO 8178-1:2020, Annex D).

It is recommended that this analysis be performed at 1 Hz. For a test to be considered valid, the criteria of Table 4 shall be met.

Table 4 — Regression line tolerances

	Speed	Torque	Power
Standard error of estimate (S_{EE}) of y on x	≤5,0 % of maximum test speed	≤10,0 % of maximum mapped torque	≤10,0 % of maximum mapped power
Slope of the regression line, a_1	0,95 to 1,03	0,83 to 1,03	0,89 to 1,03
Coefficient of determination, r^2	minimum 0,970	minimum 0,850	minimum 0,910
y intercept of the regression line, a_0	±10 % of idle	±20 Nm or ±2 % of maximum torque whichever is greater	±4 kW or ±2 % of maximum power whichever is greater

For regression purposes only, point deletions are permitted where noted in Table 5 before doing the regression calculation. However, those points shall not be deleted for the calculation of cycle work and emissions. An idle point is defined as a point having a normalized reference torque of 0 % and a normalized reference speed of 0 %. Point deletion may be applied to the whole or to any part of the cycle; points to which the point deletion is applied have to be specified.

Table 5 — Permitted point deletions from regression analysis

Event	Conditions (n = engine speed, T = torque)	Permitted point deletions
Minimum operator demand (idle point)	$n_{ref} = n_{idle}$ and $T_{ref} = 0$ % and $T_{act} > (T_{ref} - 0{,}02\ T_{maxmappedtorque})$ and $T_{act} < (T_{ref} + 0{,}02\ T_{maxmappedtorque})$	speed and power

Table 5 *(continued)*

Event	Conditions (n = engine speed, T = torque)	Permitted point deletions
Minimum operator demand	$n_{act} \leq 1{,}02\ n_{ref}$ and $T_{act} > T_{ref}$ or $n_{act} > n_{ref}$ and $T_{act} \leq T_{ref}$ or $n_{act} > 1{,}02\ n_{ref}$ and $T_{ref} < T_{act} \leq (T_{ref} + 0{,}02\ T_{maxmappedtorque})$	power and either torque or speed
Maximum operator demand	$n_{act} < n_{ref}$ and $T_{act} \geq T_{ref}$ or $n_{act} \geq 0{,}98\ n_{ref}$ and $T_{act} < T_{ref}$ or $n_{act} < 0{,}98\ n_{ref}$ and $T_{ref} > T_{act} \geq (T_{ref} - 0{,}02\ T_{maxmappedtorque})$	power and either torque or speed

Key

n_{ref}	reference speed (see 7.7.2)
n_{idle}	idle speed
n_{act}	actual (measured) speed
T_{ref}	reference torque (see 7.7.2)
T_{act}	acutal (measured) torque
$T_{maxmappedtorque}$	highest value of torque on the full-load torque curve mapped in accordance with 7.4

8.7 Post-test procedures

The following steps shall be taken after emission sampling is complete:

8.7.1 Verification of proportional sampling

For any proportional batch sample, such as a bag sample or PM sample, it shall be verified that proportional sampling was maintained according to 8.2.1. For the single filter method and the discrete steady-state test cycle, effective PM weighting factor shall be calculated. Any sample that does not fulfil the requirements of 8.2.1 shall be voided.

8.7.2 Post-test PM conditioning and weighing

Used PM sample filters shall be placed into covered or sealed containers or the filter holders shall be closed, in order to protect the sample filters against ambient contamination. Thus protected, the loaded filters have to be returned to the PM-filter conditioning chamber or room. Then the PM sample filters shall be conditioned and weighed accordingly.

8.7.2.1 Periodic verification

It shall be assured that the weighing and PM-stabilization environments have met the periodic verifications in ISO 8178-1:2020, 9.6.3. After testing is complete, the filters shall be returned to the weighing and PM-stabilisation environment. The weighing and PM-stabilisation environment shall meet the ambient conditions requirements in ISO 8178-1:2020, 8.1.5.1, otherwise the test filters shall be left covered until proper conditions have been met.

8.7.2.2 Removal from sealed containers

In the PM-stabilization environment, the PM samples shall be removed from the sealed containers. Filters may be removed from their cassettes before or after stabilization. When a filter is removed from a cassette, the top half of the cassette shall be separated from the bottom half using a cassette separator designed for this purpose. It is recommended that the top portion of the cassette be removed at the beginning of stabilisation.

8.7.2.3 Electrical grounding

To handle PM samples, electrically grounded tweezers or a grounding strap shall be used, as described in ISO 8178-1:2020, 8.1.5.3.

8.7.2.4 Visual inspection

The collected PM samples and the associated filter media shall be inspected visually. If the conditions of either the filter or the collected PM sample appear to have been compromised, or if the particulate matter contacts any surface other than the filter, the sample may not be used to determine particulate emissions. In the case of contact with another surface, the affected surface shall be cleaned before proceeding.

8.7.2.5 Stabilization of PM samples

To stabilise PM samples, they shall be placed in one or more containers that are open to the PM-stabilization environment, which is described in ISO 8178-1:2020, 8.1.5.1. A PM sample is stabilized as long as it has been in the PM-stabilization environment for one of the following durations, during which the stabilization environment has been within the specifications of ISO 8178-1:2020, 8.1.5.1:

a) If it is expected that a filter's total surface concentration of PM will be greater than 0,353 μg/mm^2, assuming a 400 μg loading on a 38 mm diameter filter stain area, the filter shall be exposed to the stabilization environment for at least 60 min before weighing. Note that 400 μg on sample media (e.g. filters) corresponds to an approximate brake specific emission of 0,07 g/kWh for a hot-start test.

b) If it is expected that a filter's total surface concentration of PM will be less than 0,353 μg/mm^2, the filter shall be exposed to the stabilization environment for at least 30 min before weighing.

c) If a filter's total surface concentration of PM to be expected during the test is unknown, the filter shall be exposed to the stabilization environment for at least 60 min before weighing.

8.7.2.6 Determination of post-test filter mass

The procedures in 8.2.3 shall be repeated (8.2.3.6 to 8.2.3.9) to determine the post-test filter mass.

8.7.2.7 Total mass

Each buoyancy-corrected filter tare mass shall be subtracted from its respective buoyancy-corrected post-test filter mass. The result is the total mass, m_{total}, which shall be used in emission calculations in Clause 9 and Annex H.

8.7.3 Analysis of gaseous batch sampling

As soon as practical, the following shall be performed:

a) All batch gas analysers shall be zeroed and spanned no later than 30 min after the test cycle is complete or during the soak period if practical to check if gaseous analysers are still stable.

b) Any conventional gaseous batch samples shall be analysed no later than 30 min after the hot-start test cycle is complete or during the soak period.

c) The background samples shall be analysed no later than 60 min after the hot-start test cycle is complete.

8.7.4 Drift verification

After quantifying exhaust gases, drift shall be verified as follows:

a) For batch and continuous gas analysers, the mean analyser value shall be recorded after stabilizing a zero gas to the analyser. Stabilization may include time to purge the analyser of any sample gas, plus any additional time to account for analyser response.

b) The mean analyser value shall be recorded after stabilizing the span gas to the analyser. Stabilization may include time to purge the analyser of any sample gas, plus any additional time to account for analyser response.

c) These data shall be used to validate and correct for drift as described in 8.2.2.

9 Data evaluation and calculation

9.1 Gaseous emissions

Calculating gaseous emissions can be conducted by the mass-based procedure in Clause 9. Alternatively, the molar-based approach according to Annex H can be applied, which is equally acceptable.

9.1.1 General

The gaseous components emitted by the engine submitted for testing shall be measured by the methods described in ISO 8178-1:2020, Clause 7. They shall be determined in the raw or dilute exhaust gas. Data evaluation and calculation procedures are described in 9.1.3 and 9.1.4.

9.1.2 Sampling for gaseous emissions

The gaseous emissions sampling probes shall be fitted at least 0,5 m or 3 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.

In the case of a multi-cylinder engine with a branched exhaust manifold, the inlet of the probe shall be located sufficiently far downstream so as to ensure that the sample is representative of the average exhaust emissions from all cylinders. In multi-cylinder engines having distinct groups of manifolds, such as in a “V” engine configuration, the manifolds should be combined upstream of the sampling probe. If this is not practical, other methods may be used (see ISO 8178-1:2020, 5.2.3). For exhaust emission calculation, the total exhaust mass flow, determined according to one of the following formulae shall be used. If the engine is equipped with an exhaust aftertreatment system, the exhaust sample shall be taken downstream of the exhaust aftertreatment system.

9.1.2.1 Air and fuel measurement method (see ISO 8178-1:2020, 6.4.4.1)

$$q_{mew,i} = q_{maw,i} + q_{mf,i} \tag{17}$$

where

$q_{maw,i}$ is instantaneous intake air mass flow rate [kg/s];

$q_{mf,i}$ is instantaneous fuel mass flow rate [kg/s].

9.1.2.2 Tracer measurement method (see ISO 8178-1:2020, 6.4.4.3)

This involves measurement of the concentration of a tracer gas in the exhaust. The calculation of the instantaneous exhaust gas flow $q_{mew,i}$ [kg/s] shall be as follows:

$$q_{mew,i} = \frac{q_{Vt} \times \rho_e}{10^{-6} \times (c_{mix,i} - c_b)} \tag{18}$$

where

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

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

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

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

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

9.1.2.3 Air flow and air-to-fuel ratio measurement method (see ISO 8178-1:2020, 6.4.4.4)

$$q_{mew,i} = q_{maw,i} \times \left(1 + \frac{1}{\frac{A}{F_{st}} \times \lambda_i} \right) \tag{19}$$

with:

$$A/F_{st} = \frac{138{,}0 \times \left(1 + \frac{\alpha}{4} - \frac{\varepsilon}{2} + \gamma \right)}{12{,}011 + 1{,}007\,94 \times \alpha + 15{,}999\,4 \times \varepsilon + 14{,}006\,7 \times \delta + 32{,}065 \times \gamma} \tag{20}$$

$$\lambda_i = \frac{\left(100 - \frac{c_{COd} \times 10^{-4}}{2} - c_{HCw} \times 10^{-4} \right) + \left(\frac{\alpha}{4} \times \frac{1 - \frac{2 \times c_{COd} \times 10^{-4}}{3{,}5 \times c_{CO2d}}}{1 + \frac{c_{COd} \times 10^{-4}}{3{,}5 \times c_{CO2d}}} - \frac{\varepsilon}{2} - \frac{\delta}{2} \right) \times \left(c_{CO2d} + c_{COd} \times 10^{-4} \right)}{4{,}764 \times \left(1 + \frac{\alpha}{4} - \frac{\varepsilon}{2} + \gamma \right) \times \left(c_{CO2d} + c_{COd} \times 10^{-4} + c_{HCw} \times 10^{-4} \right)} \tag{21}$$

where

$q_{maw,i}$ is wet intake air mass flow rate [kg/s];

A/F_{st} is stoichiometric air-to-fuel ratio [–];

λ_i is instantaneous excess air ratio [–];

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

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

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

α is molar hydrogen-to-carbon ratio [–];

δ is molar nitrogen-to-carbon ratio [–];

ε is molar oxygen-to-carbon ratio [–];

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

9.1.3 Data evaluation

For the evaluation of the gaseous emissions, the raw emission concentrations (HC, CO and NO_x) and the exhaust gas mass flow rate shall be recorded and stored with at least 2 Hz on a computer system. All other data may be recorded with a sample rate of at least 1 Hz. For analogue analysers, the response shall be recorded, and the calibration data may be applied online or offline during the data evaluation.

For calculation of the mass emission of the gaseous components the traces of the recorded concentrations and the trace of the exhaust gas mass flow rate shall be time aligned by the transformation time as defined in Clause 3. Therefore, the response time of each gaseous emissions analyser and of the exhaust gas mass flow system shall be determined according to ISO 8178-1:2020, 9.1.6.2 and 9.1.6.3, respectively, and recorded.

9.1.4 Calculation of mass emission

9.1.4.1 General

The mass of the pollutants (g/test) shall be preferably determined by calculating the instantaneous mass emissions from the raw concentrations of the pollutants, the u values from Table 6 and the exhaust mass flow, aligned for the transformation time as determined in accordance with 9.1.3, and integrating the instantaneous values over the cycle in accordance with 9.1.4.2. Preferably, the concentrations should be measured on a wet basis. If measured on a dry basis, the dry/wet correction according to 9.1.5 shall be applied to the instantaneous concentration values before any further calculation is done.

Optionally, the mass emissions may be calculated using the exact formulae of 9.1.4.3 with the prior agreement of the parties involved. The exact formulae must be used if the fuel used for the test is not specified in Table 6, under multi-fuel operation or in case of dispute.

An example of the calculation procedures is given in Annex F.

9.1.4.2 Calculation method based on tabulated values of gas properties

9.1.4.2.1 Steady state test

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

$$q_{mgas,i} = k_h \times k \times u_{gas} \times q_{mew,i} \times c_{gas,i} \times 3\,600 \quad (22)$$

where

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

k_h is NOx correction factor [–], only to be applied for the NOx emission calculation (see 9.1.5);

k equals 1 for $c_{gas,i}$ in [µmol/mol] and 10 000 for $c_{gas,i}$ in [% vol];

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

c_{gas} is the concentration of the respective component in the raw exhaust gas [µmol/mol];

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

For the calculation of NO_x, the humidity correction factor – k_{hd} or k_{hp}, as applicable and as determined according to 9.1.6 – shall be used. The measured concentration shall be converted to a wet basis according to 9.1.5, if not already measured on a wet basis. Values for u are given in Table 6 for selected components based on ideal gas properties and a range of fuels.

9.1.4.2.2 Transient and ramped-modal cycles tests

The total mass per test of a gaseous emission m_{gas} [g/test] shall be calculated by multiplication of the time aligned instantaneous concentrations and exhaust gas flows and integration over the test cycle according to the following formula:

$$m_{gas} = \frac{1}{f} \times k_h \times k \times u_{gas} \times \sum_{i=1}^{i=n} \left(q_{mew,i} \times c_{gas,i} \right) \quad (23)$$

where

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

k_h is the NO_x correction factor [–], only to be applied for the NO_x emission calculation (see 9.1.5);

k equals 1 for $c_{gas,i}$ in [µmol/mol] and 10 000 for $c_{gas,i}$ in [% vol];

$c_{gas,i}$ is the instantaneous emission concentration in the raw exhaust gas, on a wet basis [µmol/mol] or [% vol];

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

f is the data sampling rate [Hz];

n is the number of measurements.

For the calculation of NO_x, the humidity correction factor $k_{h,D}$ and $k_{h,G}$ as applicable, as determined according to 9.1.6, shall be used.

The instantaneously measured concentration shall be converted to a wet basis according to 9.1.5, if not already measured on a wet basis.

Values for u are given in Table 6 for selected components based on ideal gas properties and a range of fuels.

Table 6 — Values of *u* in the exhaust gas and density for various exhaust components

Gas		NO_x	CO	HC	CO_2	O_2	CH_4	HCHO	CH_3OH
ρ_{gas} [kg/m³]		2,053	1,250	a	1,963 6	1,427 7	0,716	1,340	1,430
FUEL	ρ_e	Coefficient u_{gas} [b]							
Diesel (non-road gas-oil)	1,294 3	0,001 586	0,000 966	0,000 482	0,001 517	0,001 103	0,000 553	0,001 035	0,001 104

a Depending on the fuel.

b At λ = 2, wet air, 273 K, 101,3 kPa.

c u accurate within 0,2 % for mass composition of: C = 66 % to 76 %; H = 22 % to 25 %; N = 0 % to 12 %.

d NMHC on the basis of $CH_{2,93}$ (for total HC the u_{gas} coefficient of CH_4 is used).

e u accurate within 0,2 % for mass composition of: C_3 = 70 – 90 %; C_4 = 10 – 30 %.

Table 6 *(continued)*

Gas		NO_x	CO	HC	CO_2	O_2	CH_4	HCHO	CH_3OH
RME	1,295 0	0,001 585	0,000 965	0,000 536	0,001 516	0,001 102	0,000 553	0,001 035	0,001 104
Methanol	1,261 0	0,001 628	0,000 991	0,001 133	0,001 557	0,001 132	0,000 568	0,001 062	0,001 134
Ethanol	1,275 7	0,001 609	0,000 980	0,000 805	0,001 539	0,001 119	0,000 561	0,001 050	0,001 121
Ethanol for dedicated compression ignition engines (ED95)	1,276 8	0,001 609	0,000 980	0,000 780	0,001 539	0,001 119	0,000 561	0,001 050	0,001 121
Ethanol (E85)	1,279 7	0,001 604	0,000 977	0,000 730	0,001 534	0,001 116	0,000 559	0,001 047	0,001 117
Natural gas / bio-methane[c]	1,266 1	0,001 621	0,000 987	0,000 528[d]	0,001 551	0,001 128	0,000 565	0,001 058	0,001 129
Propane	1,280 5	0,001 603	0,000 976	0,000 512	0,001 533	0,001 115	0,000 559	0,001 046	0,001 116
Butane	1,283 2	0,001 600	0,000 974	0,000 505	0,001 530	0,001 113	0,000 558	0,001 044	0,001 114
LPG[e]	1,281 1	0,001 602	0,000 976	0,000 510	0,001 533	0,001 115	0,000 559	0,001 046	0,001 116
Gasoline	1,297 7	0,001 582	0,000 963	0,000 481	0,001 513	0,001 100	0,000 552	0,001 032	0,001102
Petrol (E10)	1,293 1	0,001 587	0,000 966	0,000 499	0,001 518	0,001 104	0,000 553	0,001 035	0,001 105

[a] Depending on the fuel.

[b] At λ = 2, wet air, 273 K, 101,3 kPa.

[c] *u* accurate within 0,2 % for mass composition of: C = 66 % to 76 %; H = 22 % to 25 %; N = 0 % to 12 %.

[d] NMHC on the basis of $CH_{2,93}$ (for total HC the u_{gas} coefficient of CH_4 is used).

[e] *u* accurate within 0,2 % for mass composition of: C_3 = 70 – 90 %; C_4 = 10 – 30 %.

9.1.4.2.3 Full flow dilution measurement (CVS)

The exhaust mass flow rate shall be measured with a constant volume sampling (CVS) system, which may use a positive displacement pump (PDP), a critical flow venturi (CFV) or a subsonic venturi (SSV).

For systems with constant mass flow (i.e. with heat exchanger), the mass of the pollutants m_{gas} [g/test] shall be determined from the following formula:

$$m_{gas} = k_h \times k \times u_{gas} \times c_{gas} \times m_{ed} \tag{24}$$

where

- u_{gas} is the ratio between density of exhaust component and density of exhaust air (equivalent to air density), as given in Table 6 or calculated with Formula (37);
- c_{gas} is mean background corrected concentration of the component on a wet basis [µmol/mol] or [% vol] respectively;
- k_h is NO_x correction factor [–], only to be applied for the NO_x emission calculation;
- k equals 1 for $c_{gas,i}$ in [µmol/mol] and 10 000 for $c_{gas,i}$ in [% vol];
- m_{ed} is total diluted exhaust gas mass over the cycle [kg/test].

For systems with flow compensation (without heat exchanger), the mass of the pollutants m_{gas} [g/test] shall be determined by calculation of the instantaneous mass emissions, by integration and by background correction according to the following formula:

$$m_{gas} = k_h \times k \times \left\{ \sum_{i=1}^{n} \left[\left(m_{ed,i} \times c_e \times u_{gas} \right) \right] - \left[\left(m_{ed} \times c_d \times \left(1 - \frac{1}{D} \right) \times u_{gas} \right) \right] \right\} \tag{25}$$

where

c_e is emission concentration in the diluted exhaust gas, on a wet basis [µmol/mol] or [% vol];

c_d is emission concentration in the dilution air, on a wet basis [µmol/mol] or [% vol].

9.1.4.2.3.1 PDP-CVS system (see ISO 8178-1:2020, 9.8.2)

The calculation of the mass of the diluted exhaust [kg/test] over the cycle is as follows, if the temperature of the diluted exhaust med is kept within ±6 K over the cycle by using a heat exchanger:

$$m_{ed} = 1{,}293 \times V_0 \times n_p \times \frac{p_p}{101{,}3} \times \frac{273}{T} \tag{26}$$

where

V_0 is volume of gas pumped per revolution under test conditions [m^3/rev];

n_p is total revolutions of pump per test [rev/test];

p_p is absolute pressure at pump inlet [kPa];

T is average temperature of the diluted exhaust gas at pump inlet [K];

1,293 is air density [kg/m^3] at 273,15 K and 101,325 kPa.

If a system with flow compensation is used (i.e. without heat exchanger), the mass of the diluted exhaust gas $m_{ed,i}$ [kg] during the time interval shall be calculated as follows:

$$m_{ed,i} = 1{,}293 \times V_0 \times n_{P,i} \times \frac{p_p}{101{,}3} \times \frac{273}{T} \tag{27}$$

where

V_0 is volume of gas pumped per revolution under test conditions [m^3/rev];

p_p is absolute pressure at pump inlet [kPa];

$n_{P,i}$ is total revolutions of pump per time interval i [rev/Δt];

T is average temperature of the diluted exhaust gas at pump inlet [K];

1,293 is air density [kg/m^3] at 273,15 K and 101,325 kPa.

9.1.4.2.3.2 CFV-CVS system (see ISO 8178-1:2020, 9.8.3)

The calculation of the mass flow over the cycle m_{ed} [g/test] is as follows, if the temperature of the diluted exhaust is kept within ±11 K over the cycle by using a heat exchanger:

$$m_{ed} = \frac{1{,}293 \times t \times K_V \times p_p}{T^{0{,}5}} \tag{28}$$

where

t is cycle time [s];

K_V is calibration coefficient of the critical flow venturi for standard conditions $\left[\left(\sqrt{K}\times m^4\times s\right)/kg\right]$;

p_p is absolute pressure at venturi inlet [kPa];

T is absolute temperature at venturi inlet [K];

1,293 is air density [kg/m^3] at 273,15 K and 101,325 kPa.

If a system with flow compensation is used (i.e. without heat exchanger), the mass of the diluted exhaust gas $m_{ed,i}$ [kg] during the time interval shall be calculated as follows:

$$m_{ed,i}=\frac{1{,}293\times \Delta t_i\times K_V\times p_p}{T^{0,5}} \quad (29)$$

where

Δt_i is time interval of the test [s];

K_V is calibration coefficient of the critical flow venturi for standard conditions $\left[\left(\sqrt{K}\times m^4\times s\right)/kg\right]$;

p_p is absolute pressure at venturi inlet [kPa];

T is absolute temperature at venturi inlet [K];

1,293 is air density [kg/m^3] at 273,15 K and 101,325 kPa.

9.1.4.2.3.3 SSV-CVS system (see ISO 8178-1:2020, 9.8.4)

The calculation of the diluted exhaust gas mass over the cycle m_{ed} [kg/test] shall be as follows, if the temperature of the diluted exhaust is kept within ±11 K over the cycle by using a heat exchanger:

$$m_{ed}=1{,}293\times q_{VSSV}\times \Delta t \quad (30)$$

where

1,293 is air density [kg/m^3] at 273,15 K and 101,325 kPa;

Δt is cycle time [s];

q_{VSSV} is volumetric flow rate of the SSV [m^3/s] according to ISO 8178-1:2020, 9.8.4.2.

If a system with flow compensation is used (i.e. without heat exchanger), the mass of the diluted exhaust gas $m_{ed,i}$ [kg] during the time interval shall be calculated as follows:

$$m_{ed,i}=1{,}293\times q_{VSSV}\times \Delta t_i \quad (31)$$

where

1,293 is air density [kg/m^3] at 273,15 K and 101,325 kPa;

Δt_i is time interval [s];

q_{VSSV} is volumetric flow rate of the SSV [m^3/s] according to ISO 8178-1:2020, 9.8.4.2.

9.1.4.3 Calculation method based on calculated gas properties

9.1.4.3.1 Raw gaseous emissions

The mass emission shall be calculated using Formula (22). Instead of using the tabulated values, the following formulae shall be applied for the calculation of u_{gas}. It is assumed in the following formulae that the concentration c_{gas} in Formula (22) is measured in or converted to μmol/mol.

$$u_{gas,i} = M_{gas} / (M_{e,i} \times 1\,000) \tag{32}$$

or

$$u_{gas,i} = \rho_{gas} / (\rho_{e,i} \times 1\,000) \tag{33}$$

where

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

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

ρ_{gas} is density of the gas component [kg/m^3] = M_{gas} / 22,414 is optionally taken from Table 6;

$\rho_{e,i}$ is 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 6. The molecular mass of the exhaust, M_e, shall 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:

$$M_{e,i} = \frac{1 + \frac{q_{mf,i}}{q_{maw,i}}}{\frac{q_{mf,i}}{q_{maw,i}} \times \frac{\frac{\alpha}{4} + \frac{\varepsilon}{2} + \frac{\delta}{2}}{12{,}001 + 1{,}007\,94 \times \alpha + 15{,}999\,4 \times \varepsilon + 14{,}006\,7 \times \delta + 32{,}006\,5 \times \gamma} + \frac{\frac{H_a \times 10^{-3}}{2 \times 1{,}007\,94 + 15{,}999\,4} + \frac{1}{M_{r,air}}}{1 + H_a \times 10^{-3}}} \tag{34}$$

The exhaust density ρ_e shall be derived, as follows:

$$\rho_{e,i} = \frac{1\,000 + H_a + 1\,000 \times (q_{mf,i} / q_{mad,i})}{773{,}4 + 1{,}243\,4 \times H_a + K_f \times 1\,000 \times (q_{mf,i} / q_{mad,i})} \tag{35}$$

where

$$k_f = 0{,}055\,584 \times w_H - 0{,}000\,108\,3 \times w_C - 0{,}000\,156\,2 \times w_S + 0{,}007\,993\,6 \times w_N + 0{,}006\,997\,8 \times w_O \tag{36}$$

9.1.4.3.2 Diluted gaseous emissions

$$u_{gas,i} = M_{gas} / (M_{d,w} \times 1\,000) = \frac{M_{gas}}{\left[M_{da,w} \times \left(1 - \frac{1}{D}\right) + M_{r,w} \times \left(\frac{1}{D}\right)\right] \times 1\,000} \tag{37}$$

where

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

$M_{d,w}$ is molar mass of diluted exhaust gas [g/mol];

$M_{da,w}$ is molar mass of dilution air [g/mol];

$M_{r,w}$ is molar mass of raw exhaust gas [g/mol];

D is dilution factor [see Formula (50)] [–].

9.1.4.4 Calculation of NMHC and CH_4 with the non-methane cutter

The concentration of NMHC and CH_4 shall be calculated as follows for propane as calibration gas, bypassing NMC:

$$c_{NMHC} = \frac{c_{HC(w/oCutter)} \times (1 - E_{CH4}) - c_{HC(w/Cutter)}}{(E_{C2H6} - E_{CH4})} \tag{38}$$

$$c_{CH4} = \frac{c_{HC(w/Cutter)} - c_{HC(w/oCutter)} \times (1 - E_{C2H6})}{f_{RF\ CH4[THC-FID]} \times (E_{C2H6} - E_{CH4})} \tag{39}$$

The concentration of NMHC and CH_4 shall be calculated as follows for methane as calibration gas, passing though the NMC:

$$c_{NMHC} = \frac{c_{HC(w/o\ NMC)} \times (1 - E_{CH4}) - c_{HC(w/\ NMC)} \times f_{RF\ CH4[THC-FID]} \times (1 - E_{CH4})}{(E_{C2H6} - E_{CH4})} \tag{40}$$

$$c_{CH4} = \frac{c_{HC(w/\ NMC)} \times f_{RF\ CH4[THC-FID]} \times (1 - E_{CH4}) - c_{HC(w/o\ NMC)} \times (1 - E_{C2H6})}{f_{RF\ CH4[THC-FID]} \times (E_{C2H6} - E_{CH4})} \tag{41}$$

where

$c_{HC(w/Cutter)}$ is the HC concentration with the sample gas flowing through the NMC;

$c_{HC(w/oCutter)}$ is the HC concentration with the sample gas bypassing the NMC;

$f_{RF\ CH4[THC-FID]}$ is the response factor;

E_{CH4} is the methane efficiency as determined per ISO 8178-1:2020, 9.5.7;

E_{C2H6} is the ethane efficiency as determined per ISO 8178-1:2020, 9.5.7.

NOTE If a non-methane cutter is used, the system response time may exceed 10 s.

9.1.5 Dry/wet correction

All concentrations in 9.1.5. shall be converted using the following formula

$$c_w = k_w * c_d \tag{42}$$

9.1.5.1 Raw exhaust

9.1.5.1.1 Complete combustion

$$k_{w}=\left(1-\frac{1{,}244\,2\times H_{a}+111{,}19\times w_{H}\times\frac{q_{mf,i}}{q_{mad,i}}}{773{,}4+1{,}244\,2\times H_{a}+\frac{q_{mf,i}}{q_{mad,i}}\times k_{f}\times 1\,000}\right)\times 1{,}008 \qquad (43)$$

or

$$k_{w}=\left(1-\frac{1{,}244\,2\times H_{a}+111{,}19\times w_{H}\times\frac{q_{mf,i}}{q_{mad,i}}}{773{,}4+1{,}244\,2\times H_{a}+\frac{q_{mf,i}}{q_{mad,i}}\times k_{f}\times 1\,000}\right)\Bigg/\left(1-\frac{p_{r}}{p_{b}}\right) \qquad (44)$$

where

p_r is the water vapor pressure after cooling bath, kPa;

p_b is the total atmospheric pressure, kPa;

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

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

H_a is the intake air humidity, g water per kg dry air;

w_H hydrogen content of the fuel [% mass];

k_f is the fuel specific factor [see Formula (36)].

NOTE Formulae (43) and (44) are principally identical with the factor 1,008 in Formula (43) being an approximation for the more accurate denominator in Formula (44).

9.1.5.1.2 Incomplete combustion

$$k_{W}=\frac{\dfrac{1}{1+\alpha\times 0{,}005\times(c_{CO2}+c_{CO})}-k_{W1}}{1-\dfrac{p_{r}}{p_{b}}} \qquad (45)$$

where k_{W1} is the moisture in the intake air and is given by

$$k_{W1}=\frac{1{,}608\times H_{a}}{1\,000+(1{,}608\times H_{a})} \qquad (46)$$

where

p_r is the water vapor pressure after cooling bath, kPa;

p_b is the total atmospheric pressure, kPa;

α is the molar hydrogen ratio of the fuel;

c_{CO2} is the dry CO_2 concentration, % vol;

c_{CO} is the dry CO concentration, % vol;

H_a is the intake air humidity, g water per kg dry air.

9.1.5.2 Diluted exhaust gas

All concentrations measured dry shall be converted to wet concentrations by one of the following two formulae applied to formula:

$$k_{w,e} = \left[\left(1 - \frac{\alpha \times c_{CO2w}}{200}\right) - k_{w2}\right] \times 1{,}008 \quad (47)$$

or

$$k_{w,e} = \left(\frac{(1 - k_{w2}}{1 + \frac{\alpha \times c_{CO2d}}{200}}\right) \times 1{,}008 \quad (48)$$

where

$k_{w,e}$ is dry-to-wet conversion factor for the diluted exhaust gas [–];

α is molar hydrogen to carbon ratio of the fuel [–];

c_{CO2w} is concentration of CO_2 in the diluted exhaust gas on a wet basis [% vol];

c_{CO2d} is concentration of CO_2 in the diluted exhaust gas on a dry basis [% vol].

The dry to wet correction factor k_{w2} takes into consideration the water content of both intake air and dilution air:

$$k_{w2} = \frac{1{,}608 \times \left[H_d \times \left(1 - \frac{1}{D}\right) + H_a \times \left(\frac{1}{D}\right)\right]}{1000 + \left\{1{,}608 \times \left[H_d \times \left(1 - \frac{1}{D}\right) + H_a \times \left(\frac{1}{D}\right)\right]\right\}} \quad (49)$$

where

H_a is intake air humidity [g H_2O/kg dry air] (see Annex D on wet air);

H_d is dilution air humidity [g H_2O/kg dry air] (see Annex D on wet air);

D is dilution factor [see Formula (50)] [–].

9.1.5.3 Dilution factor

The dilution factor D [–] (which is necessary for the background correction and the k_{w2} calculation) shall be calculated as follows:

a) For diesel fuelled engines and LPG fuelled gas engines

$$D = \frac{F_S}{c_{CO2,e} + (c_{HC,e} + c_{CO,e}) \times 10^{-4}} \quad (50)$$

b) For natural gas fuelled gas engines

$$D=\frac{F_S}{c_{CO2,e}+(c_{NMHC,e}+c_{CO,e})\times 10^{-4}} \qquad (51)$$

where

F_S is stoichiometric factor v [–];

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

$c_{HC,e}$ is concentration of HC in the diluted exhaust gas on a wet basis [µmol/mol C_1];

$c_{NMHC,e}$ is concentration of NMHC in the diluted exhaust gas on a wet basis [µmol/mol C_1];

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

The stoichiometric factor shall be calculated as follows:

$$F_S=100\times\frac{1}{1+\frac{\alpha}{2}+3{,}76\times\left(1+\frac{\alpha}{4}\right)} \qquad (52)$$

where α is molar hydrogen to carbon ratio in the fuel [–].

Alternatively, if the fuel composition is not known, the following stoichiometric factors may be used:

— F_S (diesel) = 13,4

— F_S (LPG) = 11,6

— F_S (NG) = 9,5

— F_S (E10) = 13,3

— F_S (E85) = 11,5

If a direct measurement is made of the exhaust gas flow, the dilution factor D [–] may be calculated as follows:

$$D=\frac{q_{VCVS}}{q_{Vew}} \qquad (53)$$

where

q_{VCVS} is the volumetric flow rate of diluted exhaust gas [m^3/s];

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

9.1.5.4 Dilution air

$$k_{w,d}=(1-k_{w3})\times 1{,}008 \qquad (54)$$

with

$$k_{w3}=\frac{1{,}608\times H_d}{1\,000+1{,}608\times H_d} \qquad (55)$$

where H_d is dilution air humidity [g H_2O/kg dry air] (see D.2.2.3 on wet air).

9.1.6 NO_x correction for humidity and temperature

a) For compression-ignition engines correct for intake-air humidity using the following formula:

As the NO_x emission depends on ambient air conditions, the NO_x concentration shall be corrected for ambient air temperature and humidity with the factors $k_{h,D}$ [–] given in the following formulae. This factor is valid for a humidity range between 0 and 25 g H_2O/kg dry air.

$$k_{h,D} = \frac{15{,}698 \times H_a}{1\,000} + 0{,}832 \quad (56)$$

where H_a is 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.

$$k_{h,D} = \frac{1}{1 - 0{,}018\,2 \times (H_a - 10{,}71) + 0{,}004\,5 \times (T_a - 298)} \quad (57)$$

where

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

T_a is ambient air temperature [K].

b) For spark-ignition engines correct for intake-air humidity using the following formula:

$$k_{h,G} = 0{,}6272 + 44{,}030 \times 10^{-3} \times H_a - 0{,}862 \times 10^{-3} \times H_a^{\,2} \quad (58)$$

H_a, H_d may be derived from relative humidity measurement, dewpoint measurement, vapor pressure measurement or dry/wet bulb measurement using the generally accepted formulae.

$$H_a = \frac{621{,}8 \times \frac{\phi_a}{100} \times p_a}{p_b - p_a \times \frac{\phi_a}{100}}$$

$$H_d = \frac{621{,}8 \times \frac{RH_d}{100} \times p_d}{p_b - p_a \times \frac{RH_d}{100}} \quad (59)$$

where ϕ is the relative humidity.

9.1.7 Cycle work and specific emissions

9.1.7.1 Transient and ramped-modal cycles

Reference is made to H.5.1 and H.5.2 for raw and diluted exhaust respectively. The resulting values for power P [kW] shall be integrated over a test interval. The total work W_{act} [kWh] is calculated as follows:

$$W_{act} = \sum_{i=1}^{n} P_i \times \Delta t_i = \frac{1}{f} \times \frac{1}{3\,600} \times \frac{1}{10^3} \times \frac{2 \times \pi}{60} \sum_{i=1}^{n} (n_i \times T_i) \quad (60)$$

where

P_i is instantaneous engine power [kW];

Δt_i is the measurement interval [s]

n_i is instantaneous engine speed [rpm];

T_i is instantaneous engine torque [Nm];

W_{act} is actual cycle work [kWh];

f is data sampling rate [Hz];

n is number of measurements [–].

Where auxiliaries were fitted in accordance with Annex G there shall be no adjustment to the instantaneous engine torque. Where, according to 5.2.1 or 5.2.2 necessary auxiliaries that should have been fitted for the test are not installed, or auxiliaries that should have been removed for the test are installed, the value of T_i shall be adjusted as follows.

$$T_i = T_{i,\mathrm{meas}} + T_{i,\mathrm{AUX}} \tag{61}$$

where

$T_{i,\mathrm{meas}}$ is measured value of instantaneous engine torque;

$T_{i,\mathrm{AUX}}$ is corresponding value of torque required to drive auxiliaries determined according to 7.7.2.2.1.

The specific emissions e_{gas} [g/kWh] shall be calculated in the following ways depending on the type of test cycle.

$$e_{gas} = \frac{m_{gas}}{W_{act}} \tag{62}$$

where

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

W_{act} is cycle work [kWh].

In case of the composite NRTC, the final test result e_{gas} [g/kWh] shall be a weighted average from cold start test and hot start test by using:

$$e_{gas} = \left(\frac{(0,1 \times m_{cold}) + (0,9 \times m_{hot})}{(0,1 \times W_{act,cold}) + (0,9 \times W_{act,hot})} \right) \tag{63}$$

In case of an infrequent (periodic) exhaust regeneration (5.5.1.2.2), the specific emissions shall be corrected with the multiplicative adjustment factors k_{Mur} and k_{MDr} [Formulae (5) and (6)] or with the two separate pairs of adjustment additive factors k_{Ur} [upward factor of Formula (7)] and k_{Dr} [downward factor of Formula (8)].

Formula (63) specifies 10 % weighting factor for cold start and 90 % for hot start NRTC's. If alternative weighting factors are required by the parties involved; update the 0,9 and 0,1 for alternative weighting factors (e.g. 5 % for cold start and 95 % for hot start NRTC) in this formula.

9.1.7.2 Steady-state discrete-mode cycle

The specific emissions e_{gas} [g/kWh] are calculated as follows:

$$e_{gas} = \frac{\sum_{i=1}^{n_{\text{mode}}} \left(q_{mgas,i} \times f_{\text{WF}i} \right)}{\sum_{i=1}^{n_{\text{mode}}} \left(P_i \times f_{\text{WF}i} \right)} \tag{64}$$

where

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

n_{mode} is the number of modes in applicable discrete mode NRSC;

P_i is engine power for the mode i [kW] with $P_i = P_{\text{m},i} + P_{\text{aux},i}$ (see 7.7.1 and 5.2);

$f_{\text{WF}i}$ is weighting factor for the mode i [–].

9.1.8 NH_3 data evaluation

The average NH_3 concentration (µmol/mol/test) shall be determined by integrating the instantaneous values over the cycle. The following formula shall be applied:

$$c_{\text{NH}_3} = \frac{1}{n} \sum_{i=1}^{i=n} c_{\text{NH}_3,i} \left[\frac{\text{µmol}}{\text{mol}} \frac{1}{\text{test}} \right] \tag{65}$$

Alternatively the NH_3 concentration may be weighted by the exhaust mass flow

$$c_{\text{NH}_3} = \left[\frac{\sum_{i=1}^{i=n} c_{\text{NH}_3,i} \times \dot{m}_G}{\sum_{i=1}^{i=n} \dot{m}_G} \right] \left[\frac{\text{µmol}}{\text{mol}} \frac{1}{\text{test}} \right] \tag{66}$$

where

$c_{\text{NH3},i}$ is the instantaneous NH_3 concentration in the exhaust gas, µmol/mol;

n is the number of measurements.

For the composite NRTC, the final test result shall be determined with the following formula:

$$c_{\text{NH}_3} = \left(0{,}1 \times c_{\text{NH}_3,\text{cold}} \right) + \left(0{,}9 \times c_{\text{NH}_3,\text{hot}} \right) \tag{67}$$

where

$c_{\text{NH3,cold}}$ is the average NH_3 concentration of the cold start test, µmol/mol;

$c_{\text{NH3,hot}}$ is the average NH_3 concentration of the hot start test, µmol/mol.

For discrete-mode NRSC, the mean NH_3 concentration in the exhaust gas over the test cycle c_{NH3} [µmol/mol] shall be determined by measuring the mean concentration for each mode and weighting the result according to the weighting factors applicable to the test cycle. The following formula shall be applied:

$$c_{\text{NH}_3} = \sum_{i=1}^{i=n_{\text{mode}}} \bar{c}_{\text{NH}_3,i} \times f_{\text{WF}i} \tag{68}$$

where

$\bar{c}_{NH3,i}$ is the mean NH_3 concentration in the exhaust gas for mode i [µmol/mol];

n_{mode} is the number of modes in the test cycle;

f_{WFi} is the weighting factor for the mode i [–].

9.2 Particulate mass emission

9.2.1 General

The determination of the particulates requires a dilution system. In this clause, dilution shall be accomplished by a partial flow dilution system. The flow capacity of the dilution system shall be large enough to completely eliminate water condensation in the dilution and sampling systems, and 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 shall be between 20 °C and 52 °C (see ISO 8178-1:2020, 5.2.5) in close proximity to the entrance into the dilution tunnel.

The partial flow dilution system shall be designed to extract a proportional raw exhaust sample from the engine exhaust stream, thus responding to excursions 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 of 9.2.2 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, a particulate sampling system, particulate sampling filters, a microgram balance and a temperature and humidity controlled weighing chamber are required. The details of the system are described in ISO 8178-1:2020, 8.1.

9.2.2 Particulate sampling

In general, the particulate sampling probe shall be installed in close proximity to the gaseous emissions sampling probe, but sufficiently distant as to not cause interference. Therefore, the installation provisions of 9.1.2 also apply to particulate sampling. The sampling line shall conform to the requirements of ISO 8178-1:2020, 7.4.2.

In the case of a multi-cylinder engine with a branched exhaust manifold, the inlet of the probe shall be located sufficiently far downstream so as to ensure that the sample is representative of the average exhaust emissions from all cylinders. In multi-cylinder engines having distinct groups of manifolds, such as in a “V” engine configuration, the manifolds should be combined upstream of the sampling probe. If this is not practical, it is permissible to acquire a sample from the group with the highest particulate emission (reference to 9.1.2). Other methods which have been shown to correlate with the above methods may be used. For exhaust emission calculation, the total exhaust mass flow shall be used.

9.2.3 Data evaluation

The tare weight of the filter, as determined in accordance with 8.4.1, shall be subtracted from the gross weight of the filter, as determined according to 8.7.2, 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 shall be recorded.

With the prior approval of the parties involved, the particulate mass may be corrected for the particulate level of the dilution air, as determined in H.6.4.2, in line with good engineering practice and the specific design features of the particulate measurement system used.

9.2.4 Calculation of mass emission

The mass of particulates shall be calculated by either of the following methods. An example of the calculation procedures is given in Annex F.

9.2.4.1 Partial Flow Dilution System

The particulate emission over the cycle m_{PM} [g] based on sample ratio shall be calculated with the following formula:

$$m_{PM} = \frac{m_f}{r_s \times 1\,000} \quad (69)$$

where

m_f is particulate mass sampled over the cycle [mg];

r_s is average sample ratio over the test cycle [–].

with:

$$r_s = \frac{m_{se}}{m_{ew}} \times \frac{m_{sep}}{m_{sed}} \quad (70)$$

where

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

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

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

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

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

The particulate emission over the cycle m_{PM} [g] based on dilution ratio shall be calculated with the following formula:

$$m_{PM} = \frac{m_f}{m_{sep}} \times \frac{m_{edf}}{1000} \quad (71)$$

where

m_f is particulate mass sampled over the cycle [mg];

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

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

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

$$m_{edf} = \frac{1}{f} \times \sum_{i=1}^{n} q_{medf,i} \quad (72)$$

$$q_{medf,i} = q_{mew,i} \times r_{d,i} \quad (73)$$

$$r_{d,i} = \frac{q_{mdew,i}}{q_{mdew,i} - q_{mdw,i}} \quad (74)$$

where

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

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

$r_{d,i}$ is instantaneous dilution ratio [–];

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

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

f is data sampling rate [Hz];

n is number of measurements [–].

9.2.4.2 Full flow dilution system

The mass emission shall be calculated as follows:

$$m_{PM} = \frac{m_f}{m_{sep}} \times \frac{m_{ed}}{1\,000} \quad (75)$$

where

m_f is particulate mass sampled over the cycle [mg];

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

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

with

$$m_{sep} = m_{set} - m_{ssd} \quad (76)$$

where

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

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

9.2.4.3 Background correction

The particulate mass $m_{PM,c}$ [g] may be background corrected as follows:

$$m_{PM,c} = \left\{ \frac{m_f}{m_{sep}} - \left[\frac{m_b}{m_{sd}} \times \left(1 - \frac{1}{D} \right) \right] \right\} \times \frac{m_{ed}}{1\,000} \quad (77)$$

where

m_f is particulate mass sampled over the cycle [mg];

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

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

m_b is mass of collected background particulates of dilution air [mg];

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

D is dilution factor [see Formula (50)] [–].

9.2.4.4 Calculation for steady-state discrete-mode cycles

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

a) For partial-flow dilution, the equivalent mass flow of diluted exhaust gas shall be determined by means of the system with flow measurement shown in ISO 8178-1:2020, Figure 9:

$$q_{medf} = q_{mew} \times r_d \tag{78}$$

$$r_d = \frac{q_{mdew}}{q_{mdew} - q_{mdw}} \tag{79}$$

where

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

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

r_d is dilution ratio [–];

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

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

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

The particulate emission flow rate over the cycle q_{mPM} [g/h] shall be calculated as follows:

1) For the single-filter method

$$q_{mPM} = \frac{m_f}{m_{sep}} \times \overline{q_{medf}} \times \frac{3\,600}{1\,000} \tag{80}$$

$$\overline{q_{medf}} = \sum_{i=1}^{n} q_{medfi} \times f_{WFi} \tag{81}$$

$$m_{sep} = \sum_{i=1}^{n} m_{sepi} \tag{82}$$

where

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

m_f is particulate mass sampled over the cycle [mg];

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

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

f_{WFi} is weighting factor for the mode i [–];

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

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

n is number of measurements [–].

2) For the multiple-filter method

$$q_{mPMi} = \frac{m_{fi}}{m_{sepi}} \times \overline{q_{medfi}} \times \frac{3600}{1000} \tag{83}$$

where

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

m_{fi} is the particulate sample mass corrected at mode i [mg];

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

m_{sepi} is 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 as follows:

1) For the single-filter method

$$q_{mPM} = \left\{ \frac{m_f}{m_{sep}} - \left[\frac{m_{f,d}}{m_d} \times \sum_{i=1}^{n} \left(1 - \frac{1}{D_i} \right) \times f_{WFi} \right] \right\} \times \overline{q_{medf}} \times \frac{3\,600}{1\,000} \tag{84}$$

2) For the multiple-filter method

$$q_{mPMi} = \left\{ \frac{m_{fi}}{m_{sepi}} - \left[\frac{m_{f,d}}{m_d} \times \left(1 - \frac{1}{D} \right) \right] \right\} \times \overline{q_{medfi}} \times \frac{3\,600}{1\,000} \tag{85}$$

where

q_{mPM} is the particulate mass flow rate [g/h];

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

m_f is the particulate sample mass collected [mg];

m_{fi} is the particulate sample mass collected at mode i [mg];

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

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

$m_{f,d}$ is the particulate sample mass of the dilution air collected [mg];

m_d is the mass of the dilution air sample passed through the particulate sampling filters [kg];

D is the dilution factor [see Formula (50)] [–];

D_i is the dilution factor at mode i [see Formula (50)] [–];

f_{WFi} is the weighting factor for the mode i [–];

$\overline{q_{medf}}$ is the average equivalent diluted exhaust gas mass flow rate on wet basis [kg/s];

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

If more than one measurement is made $m_{f,d}/m_d$ shall be replaced with $\overline{m_{f,d}/m_d}$.

9.2.4.5 Transient and ramped-modal cycles

The particulate specific emissions shall be calculated with Formula (62) where e_{gas} [g/kWh] and m_{gas} [g/test] are substituted by e_{PM} [g/kWh] and m_{PM} [g/test] respectively:

$$e_{PM} = \frac{m_{PM}}{W_{act}} \tag{86}$$

where

m_{PM} is total mass of particulates emission, calculated according to 9.2.4 [g/test];

W_{act} is cycle work [kWh].

The emissions on the transient composite cycle (i.e. cold phase and hot phase) shall be calculated as shown in 9.1.7.

9.2.4.6 Steady-state discrete-mode cycle

The particulate specific emission e_{PM} [g/kWh] shall be calculated in the following way:

a) For the single-filter method

$$e_{PM} = \frac{q_{mPM}}{\sum_{i=1}^{n_{mode}} (P_i \times f_{WFi})} \tag{87}$$

where

P_i is engine power for the mode i [kW] with $P_i = P_{m,i} + P_{aux,i}$ (see 7.7.1 and 5.2);

n_{mode} is the number of modes in applicable discrete mode NRSC;

f_{WFi} is weighting factor for the mode i [–];

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

b) For the multiple-filter method

$$e_{PM} = \frac{\sum_{i=1}^{n_{\text{mode}}} (q_{mPMi} \times f_{\text{WF}i})}{\sum_{i=1}^{n_{\text{mode}}} (P_i \times f_{\text{WF}i})} \tag{88}$$

where

P_i is engine power for the mode i [kW] with $P_i = P_{\text{m},i} + P_{\text{aux},i}$ (see 7.7.1 and 5.2);

n_{mode} is the number of modes in applicable discrete mode NRSC;

$f_{\text{WF}i}$ is weighting factor for the mode i [–];

$q_{m\text{PM}i}$ is particulate mass flow rate at mode i [g/h].

9.2.5 Effective weighting factor (steady-state discrete cycles only)

For the single-filter method, the effective weighting factor, $f_{\text{WFe}i}$, for each mode shall be calculated in the following way.

$$f_{\text{WFe}i} = \frac{m_{\text{sep}i} \times \bar{q}_{m\text{edf}}}{m_{\text{sep}} \times q_{m\text{edf}i}} \tag{89}$$

$i = 1,...n$

where

$q_{m\text{edf}}$ is average equivalent diluted exhaust gas mass flow rate on wet basis [kg/s];

$q_{m\text{edf}i}$ is equivalent diluted exhaust gas mass flow rate on wet basis at mode i [kg/s];

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

$m_{\text{sep}i}$ is mass of diluted exhaust sample passed through the particulate sampling filter at mode i [kg].

The value of the effective weighting factors shall be within ±0,005 (absolute value) of the weighting factors listed in Annex A.

9.3 Adjustment for emission controls that are regenerated on an infrequent (periodic) basis

In case of engines, equipped with exhaust after-treatment systems that are regenerated on an infrequent (periodic) basis (see 5.5.1.2.2), the specific emissions of gaseous and particulate pollutants calculated according to 9.1.7 and 9.2.4 shall be corrected with either the applicable multiplicative adjustment factor or with the applicable additive adjustment factor. In the case that infrequent regeneration did not take place during the test the upward factor shall be applied (k_{MUr} or k_{Ur}). In the case that infrequent regeneration took place during the test the downward factor shall be applied (k_{MDr} or k_{Dr}). In the case of the discrete-mode cycle, where the adjustment factors have been determined for each mode they shall be applied to each mode during the calculation of the weighted emission result.

9.4 Particle number emission

9.4.1 Time alignment

For partial flow dilution systems residence time in the particle number sampling and measurement system shall be accounted for by time aligning the particle number signal with the test cycle and the exhaust gas mass flow rate according to the procedure in 9.1.3. The transformation time of the particle number sampling and measurement system shall be determined according to ISO 8178-1:2020, 8.4.3.2.

9.4.2 Determination of particle numbers for transient and ramped-modal cycles (RMC) with a partial flow dilution or raw gas sampling system

9.4.2.1 Partial flow dilution sampling system

Where particle numbers are sampled using a partial flow dilution or a raw gas sampling system according to the procedures set out in ISO 8178-1:2020, 8.3.2, the number of particles emitted over the test cycle shall be calculated by means of the following formula:

$$N = \frac{m_{\mathrm{edf}}}{1{,}293} \times k \times \bar{c}_{\mathrm{s}} \times \bar{f}_{\mathrm{r}} \times 10^{6} \quad (90)$$

where

N is number of particles emitted over the test cycle, #/test;

m_{edf} is mass of equivalent diluted exhaust gas over the cycle, determined according to 9.2.4, kg/test;

k is 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 shall be used for k in the above formula;

$\bar{c}_{\mathrm{s}}$ is average concentration of particles from the diluted exhaust gas corrected to standard conditions (273,15 K and 101,33 kPa), particles per cubic centimetre;

$\bar{f}_{\mathrm{r}}$ is mean particle concentration reduction factor of the volatile particle remover specific to the dilution settings used for the test.

$\bar{c}_{\mathrm{s}}$ shall be calculated from the following formula:

$$\bar{c}_{\mathrm{s}} = \frac{\sum_{i=1}^{i=n} c_{\mathrm{s},i}}{n} \quad (91)$$

where

$c_{\mathrm{s},i}$ is 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), particles per cubic centimetre;

n is number of particle concentration measurements taken over the duration of the test.

9.4.2.2 Raw gas sampling system

Where particle numbers are sampled using a raw gas sampling system according to the procedures set out in ISO 8178-1:2020, 8.4, the number of particles emitted over the test cycle shall be calculated by means of the following formula:

$$N = \frac{1}{f} \times \sum_{i=1}^{i=n} \left(\frac{q_{\mathrm{mew},i}}{\rho_{\mathrm{e},i}} \times c_{\mathrm{s},i} \right) \times k \times \overline{f_{\mathrm{r}}} \times 10^6 \quad (91a)$$

where

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

$q_{\mathrm{mew},i}$ is the instantaneous exhaust gas flow rate on a wet basis [kg/s];

$\rho_{\mathrm{e,i}}$ is the instantaneous density of the exhaust gas in the standard conditions (273,15 K and 101,33 kPa) and on a wet basis [kg/m3] [refer to Formulae (35) and (36)];

k is 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 shall be used for k in the above formula;

$\overline{f_{\mathrm{r}}}$ is the mean particle concentration reduction factor of the volatile particle remover specific to the dilution settings used for the test;

$c_{\mathrm{s},i}$ is 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), particles per cubic centimetre;

n is the number of particle concentration measurements taken over the duration of the test;

f is the data sampling rate [Hz].

9.4.3 Determination of particle numbers for transient and ramped-modal cycles (RMC) with a full flow dilution system

Where particle numbers are sampled using a full flow dilution system according to the procedures set out in ISO 8178-1:2020, 8.3.3, the number of particles emitted over the test cycle shall be calculated by means of the following formula:

$$N = \frac{m_{\mathrm{ed}}}{1{,}293} \times k \times \bar{c}_{\mathrm{s}} \times \overline{f_{\mathrm{r}}} \times 10^6 \quad (92)$$

where

N is number of particles emitted over the test cycle, #/test;

m_{ed} is total diluted exhaust gas flow over the cycle calculated according to the method described in 9.1.4.2.3, kg/test;

k is 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 shall be used for k in the above formula;

$\bar{c}_s$ is average corrected concentration of particles from the diluted exhaust gas corrected to standard conditions (273,15 K and 101,33 kPa), particles per cubic centimetre;

$\bar{f}_r$ is mean particle concentration reduction factor of the volatile particle remover specific to the dilution settings used for the test.

$\bar{c}_s$ shall be calculated from the following formula:

$$\bar{c}_s \frac{\sum_{i=1}^{i=n} c_{s,i}}{n} \quad (93)$$

where

$c_{s,i}$ is 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), particles per cubic centimetre;

n is number of particle concentration measurements taken over the duration of the test.

9.4.4 Determination of particle numbers for discrete-mode cycles with partial flow dilution or raw gas sampling system

9.4.4.1 Partial flow dilution system

Where particle numbers are sampled using a partial flow dilution system according to the procedures set out in ISO 8178-1:2020, 8.3.2, the rate emission particles during each individual discrete mode shall be calculated by means of the Formula (94) using average values for the mode:

$$\dot{N} = \frac{q_{medf}}{1,293} \times k \times \bar{c}_s \times \bar{f}_r \times 10^6 \times 3\,600 \quad (94)$$

where

$\dot{N}$ is the rate of emission of particles during the individual discrete mode, #/h;

q_{medf} is the equivalent diluted exhaust mass flow rate on a wet basis during the individual discrete mode, determined according to Formula (78), kg/s;

k is 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 shall be used for k in the above formula;

$\bar{c}_s$ is 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), particles per cubic centimetre;

$\bar{f}_r$ is the mean particle concentration reduction factor of the volatile particle remover specific to the dilution settings used for the test.

with

$$\bar{c}_s = \frac{\sum_{i=1}^{i=n} c_{s,i}}{n} \quad (95)$$

where

$c_{s,i}$ is 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), particles per cubic centimetre;

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

9.4.4.2 Raw gas sampling system

Where particle numbers are sampled using a raw gas sampling system according to the procedures set out in ISO 8178-1:2020, 8.4, the rate emission particles during each individual discrete mode shall be calculated by means of the following formula using average values for the mode:

$$\dot{N} = \frac{q_{mew}}{\rho_e} \times k \times \overline{c_s} \times \overline{f_r} \times 10^6 \times 3\,600 \qquad (96)$$

where

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

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

k is 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 shall be used for k in the above formula;

ρ_e is 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 Formulae (35) and (36)];

$\overline{c_s}$ is 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), particles per cubic centimetre;

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

with

$$\overline{c_s} = \frac{\sum_{i=1}^{n} c_{s,i}}{n} \qquad (97)$$

where

$C_{s,i}$ is a discrete measurement of particle concentration in the raw exhaust gas from the particle counter, corrected for coincidence and to standard condition (273,15 K and 101,33 kPa), particles per cubic centimetre;

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

9.4.5 Determination of particle numbers for discrete-mode cycles with a full flow dilution system

Where particle numbers are sampled using a full flow dilution system according to the specifications set out in ISO 8178-1:2020, 8.3.3 the rate of emission of particles during each individual discrete mode shall be calculated by means of the following formula using the average values for the mode:

$$\dot{N}=\frac{q_{mdew}}{1{,}293}\times k\times \bar{c}_{\mathrm{s}}\times \bar{f}_{\mathrm{r}}\times 10^{6}\times 3\,600 \qquad (98)$$

where

$\dot{N}$	is the rate of emission of particles during the individual discrete mode, #/h;
q_{mdew}	is the total diluted exhaust mass flow rate on a wet basis during the individual discrete mode, kg/s;
k	is 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 shall be used for k in the above formula;
$\bar{c}_{\mathrm{s}}$	is 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), particles per cubic centimetre;
$\bar{f}_{\mathrm{r}}$	is the mean particle concentration reduction factor of the volatile particle remover specific to the dilution settings used for the test.

with

$$\bar{c}_{\mathrm{s}}=\frac{\sum_{i=1}^{i=n} c_{\mathrm{s},i}}{n} \qquad (99)$$

where

$c_{\mathrm{s},i}$	is 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), particles per cubic centimetre;
n	is the number of particle concentration measurements taken during the individual discrete mode sampling period.

9.4.6 Test result

9.4.6.1 Calculation of the specific particle number emissions for transient and ramped-modal cycles (RMC)

For each applicable individual RMC, hot NRTC and cold NRTC the specific emissions in number of particles/kWh shall be calculated as follows:

$$e_{\mathrm{PN}}=\frac{N}{W_{\mathrm{act}}} \qquad (100)$$

where

e_{PN} is the number of particles emitted per kWh;

N is number of particles emitted over the applicable RMC, hot NRTC or cold NRTC;

W_{act} is the actual cycle work according to 8.6.3.5, in kWh.

For an RMC, in case of an engine with infrequent (periodic) exhaust regeneration (see 5.5.1.2.2), the specific emissions shall be corrected with the appropriate multiplicative adjustment factors k_{MUr} and k_{MDr} [Formulae (5) and (6)] or with the appropriate additive factors k_{Ur} [upward factor of Formula (7)] and k_{Dr} [downward factor of Formula (8)]. In the case that infrequent regeneration did not take place during the test the upward factor shall be applied (k_{MUr} or k_{Ur}). In the case that infrequent regeneration took place during the test the downward factor shall be applied (k_{MDr} or k_{Dr}).

The result, where applicable, shall also be adjusted by the infrequent regeneration adjustment factor established according to 5.5.1.2.

9.4.6.2 Weighted average NRTC test result

For the NRTC, the final test result shall be a weighted average from cold start and hot start (including periodic regeneration where relevant) tests calculated using one of the following formulae:

a) In the case of multiplicative regeneration adjustment, or engines without periodically regenerating after-treatment

$$e_{gas} = k_r \times \left(\frac{(0{,}1 \times N_{cold}) + (0{,}9 \times N_{hot})}{(0{,}1 \times W_{act,cold}) + (0{,}9 \times W_{act,hot})} \right) \tag{101}$$

b) In the case of additive regeneration adjustment

$$e_{gas} = k_r + \left(\frac{(0{,}1 \times N_{cold}) + (0{,}9 \times N_{hot})}{(0{,}1 \times W_{act,cold}) + (0{,}9 \times W_{act,hot})} \right) \tag{102}$$

where

N_{cold} is the total number of particles emitted over the NRTC cold test cycle;

N_{hot} is the total number of particles emitted over the NRTC hot test cycle;

$W_{act,cold}$ is the actual cycle work over the NRTC cold test cycle according to 9.1.7, in kWh;

$W_{act, hot}$ is the actual cycle work over the NRTC hot test cycle according to 9.1.7, in kWh;

k_r is the regeneration adjustment, according to 5.5.1.2, or in the case of engines without periodically regenerating after-treatment k_r = 1.

In the case that infrequent regeneration did not take place during the test the upward factor shall be applied (k_{MUr} or k_{Ur}). In the case that infrequent regeneration took place during the test the downward factor shall be applied (k_{MDr} or k_{Dr}).

The result, where applicable, shall also be adjusted by the infrequent regeneration adjustment factor established according to 5.5.1.2.

Formulae (101) and (102) specify a 10 % weighting factor for cold start and 90 % for hot start NRTC's. If alternative weighting factors are required by the parties involved; update the 0,9 and 0,1 for alternative weighting factors (e.g. 5 % for cold start and 95 % for hot start NRTC) in both formulae.

9.4.6.3 Calculation of the specific emissions for discrete-mode NRSC tests

The specific emissions e [#/kWh] are calculated as follows:

$$e = \frac{\sum_{i=1}^{n_{\text{mode}}} (\dot{N}_i \times f_{\text{WF}i})}{\sum_{i=1}^{n_{\text{mode}}} (P_i \times f_{\text{WF}i})} \tag{103}$$

where

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

$f_{\text{WF}i}$ is the weighting factor for the mode i [−];

$\dot{N}_i$ is the mean emission number flow rate for the mode i [#/h] from Formula (96) or (98) depending upon the dilution method.

In case of an engine with infrequent (periodic) exhaust after-treatment system regeneration (see 5.5.1.2.2), the specific emissions shall be corrected with either the applicable multiplicative adjustment factor or with the applicable adjustment additive factor. In the case that infrequent regeneration did not take place during the test the upward factor shall be applied (k_{MUr} or k_{Ur}). In the case that infrequent regeneration took place during the test the downward factor shall be applied (k_{MDr} or k_{Dr}).

Where the adjustment factors have been determined for each mode, they shall be applied to each mode during the calculation of the weighted emission result at Formula (103).

The result, where applicable, shall also be adjusted by the infrequent regeneration adjustment factor established according to 5.5.1.2.

9.4.6.4 Rounding of final results

The final NRSC and weighted average NRTC test results shall be rounded in one step to three significant figures in accordance with ASTM E29-06b. No rounding of intermediate values leading to the final brake specific emission result is permissible.

9.4.7 Determination of particle number background

At the engine manufacturer's request, dilution tunnel background particle number concentrations may be sampled, prior to or after the test, from a point downstream of the particle and hydrocarbon filters into the particle number measurement system, to determine the tunnel background particle concentrations.

Subtraction of particle number tunnel background concentrations shall not be allowed for type approval, but may be used at the manufacturer's request, with the prior approval of the parties involved, for conformity of production testing, if it can be demonstrated that tunnel background contribution is significant, which can then be subtracted from the values measured in the diluted exhaust.

9.5 Specific requirements for dual-fuel engines

For engines that do not conform to the definition in 3.17 but are operated on multiple fuels use good engineering practice to agree with the parties involved.

9.5.1 Emission test procedure requirements for dual-fuel engines

9.5.1.1 General

This clause defines the additional requirements and exceptions of this document to enable emission testing of dual-fuel engines independent whether these emissions are solely exhaust emissions or also crankcase emissions added to the exhaust emissions according to 5.5.2.

Emission testing of a dual-fuel engine is complicated by the fact that the fuel used by the engine can vary between pure liquid fuel and a combination of mainly gaseous fuel with only a small amount of liquid fuel as an ignition source. The ratio between the fuels used by a dual-fuel engine can also change dynamically depending of the operating condition of the engine. As a result, special precautions and restrictions are necessary to enable emission testing of these engines.

9.5.1.2 Test conditions (see Clause 5)

9.5.1.2.1 Laboratory test conditions (see 5.1.1)

The parameter f_a for dual-fuel engines shall be determined with Formulae (1) and (2).

9.5.1.3 Test procedures (Clause 8)

9.5.1.3.1 Measurement procedures

A full-flow dilution measurement procedure for dual-fuel engines is described in ISO 8178-1:2020, 8.3.3 (CVS system).

This measurement procedure ensures that the variation of the fuel composition during the test will mainly influence the hydrocarbon measurement results. This shall be compensated via one of the methods described in 9.5.1.4.

Raw gaseous/partial flow measurement described in ISO 8178-1:2020, 8.3.2 may be used with some precautions regarding exhaust mass flow determination and calculation methods.

9.5.1.4 Emission calculation

The emission calculation requires knowledge of the composition of the fuels being used. When a gaseous fuel is supplied with a certificate confirming the properties of the fuel (e.g. gas from bottles) it is acceptable to use the composition specified by the supplier. Where the composition is not available (e.g. pipeline fuel) the fuel composition shall be analysed at least prior to and after the engine emission test is conducted. More frequent analysis shall be permitted and the results used in the calculation.

Where the gas energy ratio (GER) is used it shall be consistent with the definition in 3.25. The average value of GER over the cycle shall be calculated by one of the following methods:

a) For hot-start transient cycle and RMC NRSC by dividing the sum of the GER at each measurement point by the number of measurement points.

b) For discrete-mode NRSC by multiplying the average GER for each test mode by the corresponding weighting factor for that mode and calculating the sum for all modes. The weighting factors shall be taken from Annex A for the applicable cycle.

9.5.1.4.1 Dry/wet correction (see 9.1.5)

9.5.1.4.1.1 Raw exhaust gas

Formulae (45) and (46) shall be used to calculate the dry/wet correction.

The fuel specific parameters shall be determined according to 9.5.2.2.

9.5.1.4.1.2 Diluted exhaust gas

Formulae (48) and (49) shall be used to calculate the wet/dry correction.

The molar hydrogen ratio α of the combination of the two fuels shall be used for the dry/wet correction. This molar hydrogen ratio shall be calculated from the fuel consumption measurement values of both fuels according to 9.5.2.

9.5.1.4.2 NO_x correction for humidity (see 9.1.6)

The NO_x humidity correction for compression ignition engines as specified in 9.1.6 shall be used to determine the NO x humidity correction for dual-fuel engines.

9.5.1.4.3 Partial flow dilution (PFS) and raw gaseous measurement (ISO 8178-1:2020, 8.3.2)

9.5.1.4.3.1 Determination of exhaust gas mass flow (ISO 8178-1:2020, 6.4.3)

The exhaust mass flow shall be determined according to the direct measurement method as described in ISO 8178-1:2020, 6.4.3.

Alternatively, the airflow and air to fuel ratio measurement method according to ISO 8178-1:2020, 6.4.4.4 and 9.1.2.3 [Formulae (19) to (21)] may be used only if α, γ, δ and ε values are determined according to 9.5.2.2.2. The use of a zirconia-type sensor to determine the air fuel ratio is not allowed.

Exhaust gas mass flow rate calculation based on air flow and fuel flow measurements (ISO 8178-1:2020, 6.4.4.1) may alternatively be used for steady-state testing.

For raw gaseous measurement, exhaust mass flow may be calculated based on the fuel flow and carbon balance method (D.3.2.3.1), when the test mode is of a steady-state discrete mode type.

9.5.1.4.3.2 Determination of the gaseous components (see 9.1.4)

The possible variation of fuel composition will influence all the regulated u-factors (see 9.1.4.2.2, Table 6) used in the emission calculations. One of the following approaches shall be used at the choice of the manufacturer.

a) the exact formulae in 9.1.4.3 of the mass based emission calculations or corresponding chemical balance approach provided in the molar based emission calculations in H.5.1 shall be applied using the instantaneous proportions of liquid and gaseous fuel determined from instantaneous fuel consumption measurements or calculations; or

b) when the mass-based calculation in 9.1.4.3 is used for the specific case of a dual-fuel engine operated on gas and diesel fuel, tabulated values may be used for the molar component ratios and u_{gas}-values. These tabulated values shall be applied as follows:

   1) For engines operated on the applicable test cycle with an average gas energy ratio ≥90 % (GER ≥ 0,9) the required values shall be those for gaseous fuel, taken from Table 6.

   2) For engines operated on the applicable test cycle with an average gas energy ratio between 10 % and 90 % (0,1 < GER < 0,9) the required values shall be assumed to be represented by those for a mixture of 50 % gaseous fuel and 50 % diesel fuel taken from Table 7 and Table 8.

   3) For engines operated on the applicable test cycle with an average gas energy ratio ≤10 % (GER ≤ 0,1) the required values shall be those for diesel fuel, taken from Table 6).

   4) For the calculation of THC emissions the u_{gas} value of the gaseous fuel shall be used in all cases irrespective of the average gas ratio (GER).

   5) For the calculation of the NMHC emissions, the u_{gas} value on the basis of $CH_{2,93}$ shall be used; in all cases irrespective of the average gas ratio (GER).

   6) For the calculation of the CH_4 emissions, the u gas value of CH_4 shall be used; in all cases irrespective of the average gas ratio (GER).

Table 7 — Molar component ratios for a mixture of 50 % gaseous fuel and 50 % diesel fuel (mass %)

Gaseous fuel	α	γ	δ	ε
CH_4	2,868 1	0	0	0,004 0
G_R	2,767 6	0	0	0,004 0
G_{23}	2,798 6	0	0,070 3	0,004 3
G_{25}	2,737 7	0	0,131 9	0,004 5
Propane	2,263 3	0	0	0,003 9
Butane	2,183 7	0	0	0,003 8
LPG	2,195 7	0	0	0,003 8
LPG Fuel A	2,174 0	0	0	0,003 8
LPG Fuel B	2,240 2	0	0	0,003 9

Table 8 — Raw exhaust gas u_{gas} values and component densities for a mixture of 50 % gaseous fuel and 50 % diesel fuel (mass %)

Gaseous fuel	ρ_e	Gas					
		NO_x	CO	HC	CO_2	O_2	CH_4
				ρ_{gas} [kg/m^3]			
		2,053	1,250	[a]	1,963 6	1,427 7	0,716
				u_{gas} [b]			
CNG/LNG[c]	1,278 6	0,001 606	0,000 978	0,000 528[d]	0,000 153 6	0,001 117	0,000 560
Propane	1,286 9	0,001 596	0,000 972	0,000 510	0,000 152 7	0,001 110	0,000 556
Butane	1,288 3	0,001 594	0,000 971	0,000 503	0,000 152 5	0,001 109	0,000 556
LPG[e]	1,288 1	0,001 594	0,000 971	0,000 506	0,000 152 5	0,001 109	0,000 556

[a] Depending on fuel.

[b] At λ = 2, dry air, 273 K, 101,3 kPa.

[c] u accurate within 0,2 % or mass composition of: C = 58 % to 76 %; H = 19 % to 25 %; N = 0 % to 14 % (CH_4, G_{20}, G_R, G_{23} and G_{25}).

[d] NMHC on the basis of $CH_{2,93}$ (for total HC the u_{gas} coefficient of CH_4 shall be used).

[e] u accurate within 0,2 % for mass composition of: C_3 = 27 % to 90 %; C_4 = 10 % to 73 % (LPG Fuels A and B).

9.5.1.4.3.3 Mass per test of a gaseous emission

In the case that the exact formulae are applied to calculate instantaneous values of u_{gas} according to 9.5.1.4.3.2 a) then, when calculating the mass per test of a gaseous emission for a transient or ramped-modal cycle, u_{gas} shall be included in the summation in Formula (23) as follows:

$$m_{gas} = \frac{1}{f} \cdot k_h \cdot k \cdot \sum_{i=1}^{n} \left(u_{gas,i} \cdot q_{mew,i} \cdot c_{gas,i} \right) \tag{104}$$

where $u_{gas,i}$ is instantaneous value of u_{gas}.

The remaining terms of the formula are as set out in 9.1.4.2.2.

9.5.1.4.3.4 Particulate determination (9.2)

For the determination of particulate emissions with the partial dilution measurement method the calculation shall be performed according to 9.2.4.

The requirements of 8.2.1.2 shall apply for controlling the dilution ratio. In particular, if the combined transformation time of the exhaust flow measurement and the partial flow system exceeds 0,3 s, look-ahead control based on a pre-recorded test run shall be used. In this case, the combined rise time shall be ≤1 s and the combined delay time ≤10 s. Except in the case that the exhaust mass flow is measured directly the determination of exhaust mass flow shall use values of α, γ, δ and ε determined according to 9.5.2.2.2.

The quality check according to 8.2.1.2 shall be performed for each measurement.

9.5.1.4.3.5 Additional requirements regarding the exhaust gas mass flow meter

The flow meter referred to in ISO 8178-1:2020, 6.4.3.1 shall not be sensitive to the changes in exhaust gas composition and density. The small errors of e.g. pitot tube or orifice-type of measurement (equivalent with the square root of the exhaust density) may be neglected.

9.5.1.5 Full flow dilution measurement (CVS) (8.2.1.1)

The possible variation of the fuel composition will mainly influence the tabulated hydrocarbon u-value (Table 6) used with the mass based formulae in Clause 9. The exact formulae shall be applied for the calculation of the hydrocarbon emissions using the molar component ratios determined from the fuel consumption measurements of both fuels according to 9.5.2.

9.5.1.5.1 Determination of the background corrected concentrations (ISO 8178-1:2020, 5.2.5)

To determine the stoichiometric factor, the molar hydrogen ratio α of the fuel shall be calculated as the average molar hydrogen ratio of the fuel mix during the test according to 9.5.2.

Alternatively the F_S value (see 9.1.5.3) of the gaseous fuel may be used in the Formulae (50) and (51).

9.5.1.6 Equipment specification and verification

9.5.1.6.1 Water quench check (ISO 8178-1:2020, 9.5.9.1.5)

The water quench check in ISO 8178-1:2020, 9.5.9.1.5 shall likewise be performed for dual-fuel engines.

9.5.2 Determination of molar component ratios and u_{gas} values for dual-fuel engines

9.5.2.1 General

This clause defines the determination of molar component ratios and u_{gas} values for the dry-wet factor and emissions calculations for emission testing of dual-fuel engines.

9.5.2.2 Determination of the molar component ratios when the fuel mix is known

9.5.2.2.1 Calculation of the fuel mixture components

The following formulae have to be used to calculate the elemental composition of the fuel mixture:

$$q_{mf} = q_{mf1} + q_{mf2} \tag{105}$$

$$w_H = \frac{w_{H1} \times q_{mf1} + w_{H2} \times q_{mf2}}{q_{mf1} + q_{mf2}} \tag{106}$$

$$w_C = \frac{w_{C1} \times q_{mf1} + w_{C2} \times q_{mf2}}{q_{mf1} + q_{mf2}} \tag{107}$$

$$w_S = \frac{w_{S1} \times q_{mf1} + w_{S2} \times q_{mf2}}{q_{mf1} + q_{mf2}} \quad (108)$$

$$w_N = \frac{w_{N1} \times q_{mf1} + w_{N2} \times q_{mf2}}{q_{mf1} + q_{mf2}} \quad (109)$$

$$w_O = \frac{w_{O1} \times q_{mf1} + w_{O2} \times q_{mf2}}{q_{mf1} + q_{mf2}} \quad (110)$$

where

q_{mf1} is fuel mass flow rate of fuel1, kg/s;

q_{mf2} is fuel mass flow rate of fuel2, kg/s;

w_H is hydrogen content of fuel, % mass;

w_C is carbon content of fuel, % mass;

w_S is sulphur content of fuel, % mass;

w_N is nitrogen content of fuel, % mass;

w_O is oxygen content of fuel, % mass.

9.5.2.2.2 Calculation of the molar ratios of H, C, S, N and O related to C for the fuel mixture

The calculation of the atomic ratios (especially the H/C-ratio α) is given in D.2.2.2 as follows:

$$\alpha = 11{,}916\,4 \times \frac{w_H}{w_C} \quad (111)$$

$$\gamma = 0{,}374\,64 \times \frac{w_S}{w_C} \quad (112)$$

$$\delta = 0{,}857\,52 \times \frac{w_N}{w_C} \quad (113)$$

$$\varepsilon = 0{,}750\,72 \times \frac{w_O}{w_C} \quad (114)$$

where

w_H is hydrogen content of fuel, % mass;

w_C is carbon content of fuel, % mass;

w_S is sulphur content of fuel, % mass;

w_N is nitrogen content of fuel, % mass;

w_O is oxygen content of fuel, % mass;

α is molar hydrogen ratio (H/C);

γ is molar sulphur ratio (S/C);

δ is molar nitrogen ratio (N/C);

ε is molar oxygen ratio (O/C).

referring to a fuel $CH_\alpha O_\varepsilon S_\gamma N_\delta$.

9.5.2.2.3 Calculation of the u_{gas} values for a fuel mixture

The raw exhaust gas u_{gas} values for a fuel mixture can be calculated with the exact formulae in 9.1.4.3 and the molar ratios calculated according to this clause.

For systems with constant mass flow, Formula (32) is needed to calculate the diluted exhaust gas u_{gas} values.

10 Engine control area

10.1 General remarks

The exhaust emissions are measured using the appropriate test cycles in accordance with 7.5 to 7.7. The emission results will therefore be representative for the respective test cycle. In addition, where it is required that the emissions from certain engine families or groups shall be controlled in areas not covered by the test cycle, this clause shall apply. While this document does not specify any conformity factor for those areas, it defines the engine control area depending on the engine operation described in 7.6 and 7.7.

Mechanically controlled engines with a fixed injection timing may not be designed to comply with a conformity factor in (certain ranges of) the emission control area.

NOTE Engine control area-standards do not apply to constant or variable-speed marine engines with a cylinder capacity greater than 30 l.

10.2 Control area for engines tested to cycles C1, C2, E1 and H

These engines operate with variable speed and load. The control area, as shown in Figure 6 and Figure 7, is defined as follows:

— upper torque limit: full load torque curve;

— speed range: speed A to n_{hi};

— torque range: 30 % to 100 %;

where:

— speed A = n_{lo} + 0,15 (n_{hi} − n_{lo});

— speed B = n_{lo} + 0,50 (n_{hi} − n_{lo});

— speed C = n_{lo} + 0,75 (n_{hi} − n_{lo});

with

— n_{lo} low speed (see 3.37);

— n_{hi} high speed (see 3.31).

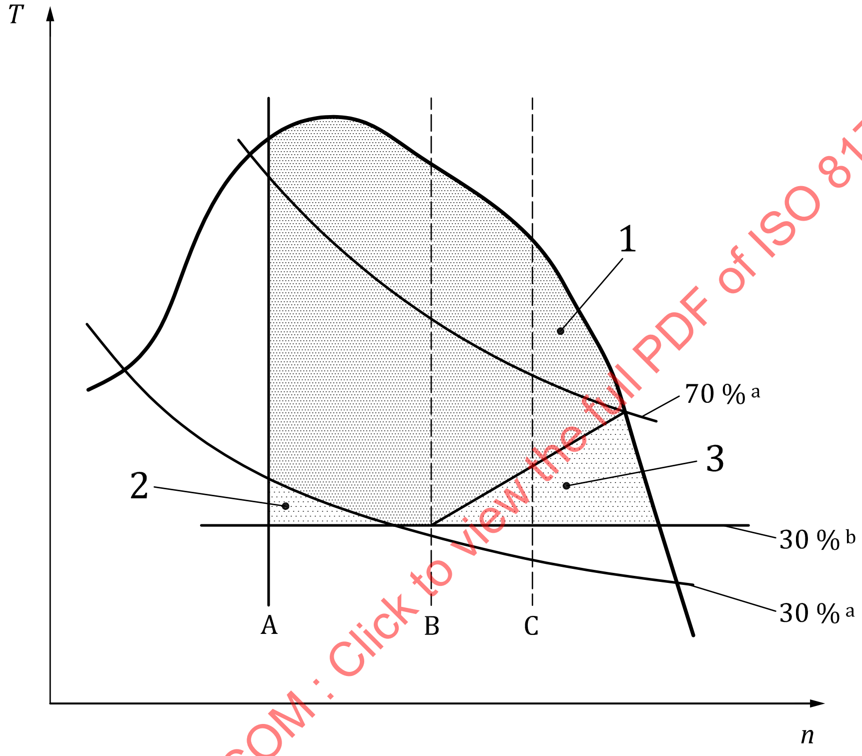
If the measured engine speeds A, B and C are within ±3 % of the engine speeds declared by the manufacturer, the declared engine speeds shall be used. If the tolerance is exceeded for any of the test speeds, the measured engine speeds shall be used.

The following speed and torque points shall be excluded from the control area:

— points below 30 % of maximum power;

— for particulate matter only, if the C speed is below 2 400 r/min, points to the right of or below the line formed by connecting the points of 30 % of maximum torque or 30 % of maximum power, whichever is greater, at the B speed and 70 % of maximum power at the high speed;

— for particulate matter only, if the C speed is above 2 400 r/min, points to the right of the line formed by connecting the points of 30 % of maximum torque or 30 % of maximum power, whichever is greater, at the B speed, 50 % of maximum power at 2 400 r/min, and 70 % of maximum power at the high speed.



Key

n speed (%)

T torque (% of maximum)

1 engine control area

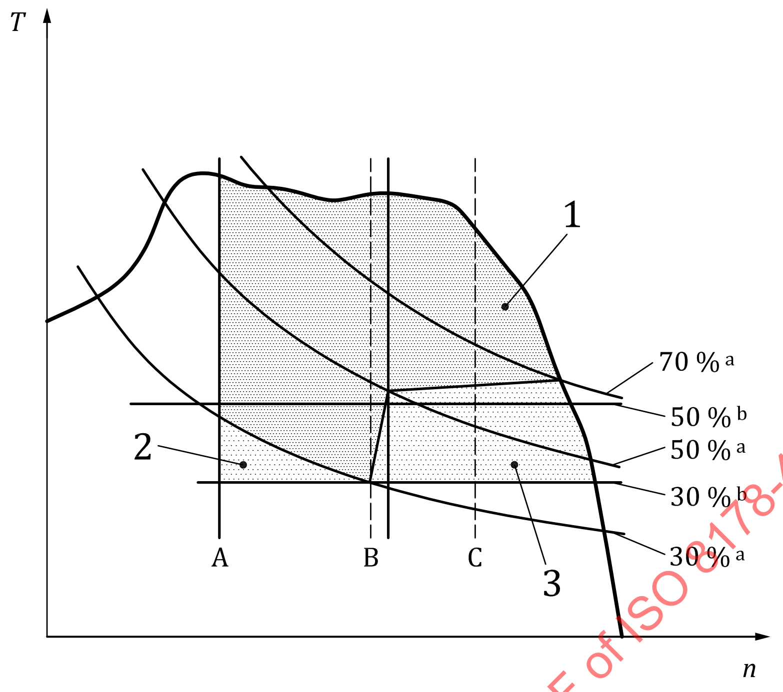
2 all emissions carve-out

3 PM carve-out

a % of maximum net power.

b % of maximum torque.

Figure 6 — Engine control area for Engines tested to cycles C1, C2, E1 and H, speed C < 2 400 rpm



Key

n speed (%)

T torque (% of maximum)

1 engine control area

2 all emissions carve-out

3 PM carve-out

[a] % of maximum net power.

[b] % of maximum torque.

Figure 7 — Engine control area for Engines tested to cycles C1, C2, E1 and H, speed C > 2 400 rpm

10.3 Control area for engines tested to cycles D1, D2, E2, G1, G2 and G3

These engines are mainly operated very close to their designed operating speed, hence the control area is defined as:

— speed: 100 %

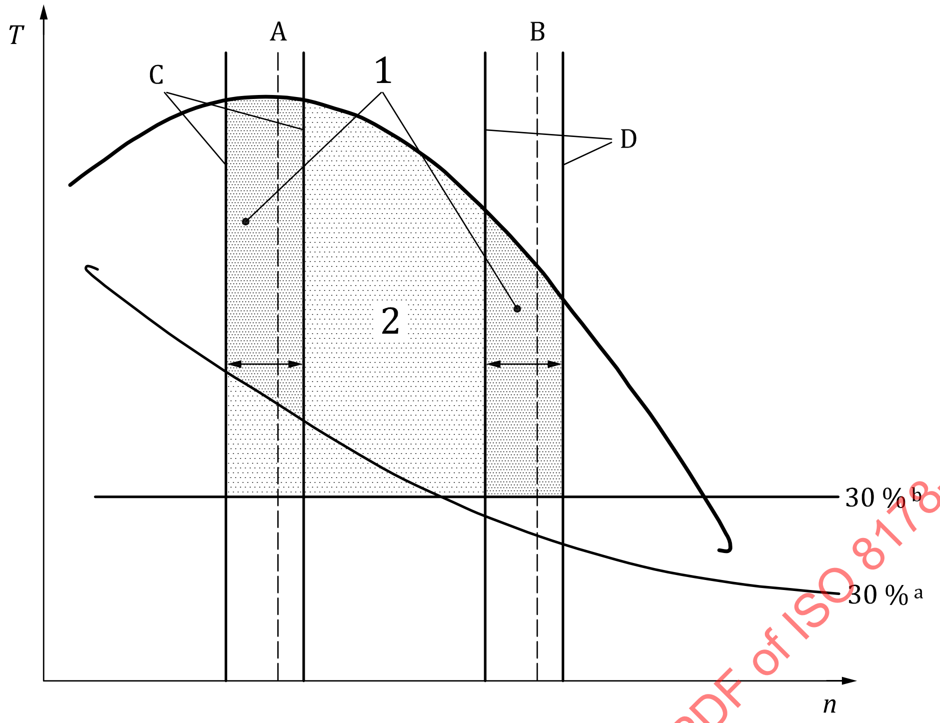
— load: 50 % to 100 %.

10.4 Control area for engines tested to test cycle I

These engines are mainly operated very close to two designated operating speeds, i.e. rated speed and intermediate speed, the control area is defined as,

— Speed: operating speeds (i.e. rated speed and intermediate speed) within the speed drop tolerance specified by the engine manufacturer.

— Load: 30 % of maximum power or 30 % of maximum torque, whichever larger, to 100 % or declared by manufacturer.



Key

n	speed (%)	D	upper and lower tolerances for speed B (example)
T	torque (% of maximum)	1	engine control area
A	intermediate speed	2	all emissions carve-out
B	rated speeds	a	Max power.
C	upper and lower tolerances for speed A (example)	b	Max torque.

Figure 8 — Engine control for Engines tested to test cycle I

10.5 Control area for engines tested to E3 and E5 test cycle

10.5.1 Control area for CI marine engines

These engines are mainly operated slightly above and below a fixed pitch propeller curve. The control area is related to the propeller curve and has exponents of mathematical formulae defining the boundaries of the control area.

For E3 cycle marine engines (see Figure 9):

a) Engine control area subzone A is defined by:

— upper boundary curve: $P_{\text{max, rel}} = 100 \times (n_{100\%,\text{ rel}}/90)^{3,5}$;

— lower boundary curve: $P_{\text{max, rel}} = 70 \times (n_{100\%,\text{ rel}}/100)^{2,5}$;

— upper power limit: Full load power curve.

b) Engine control area subzone B is defined by:

— lower speed limit: $0{,}7 \times n_{100\%}$;

— upper boundary curve: $P_{\text{max, rel}} = 100 \times (n_{100\%,\text{ rel}}/90)^{3,5}$;

— lower boundary curve: $P_{\text{max, rel}} = 70 \times (n_{100\%,\text{ rel}}/100)^{2,5}$.

c) Line separating engine control area subzone A and B is defined by the following end-point coordinates:

— $n_{100\%,\,rel}$: 78,9; $P_{max,\,rel}$ 63,2;

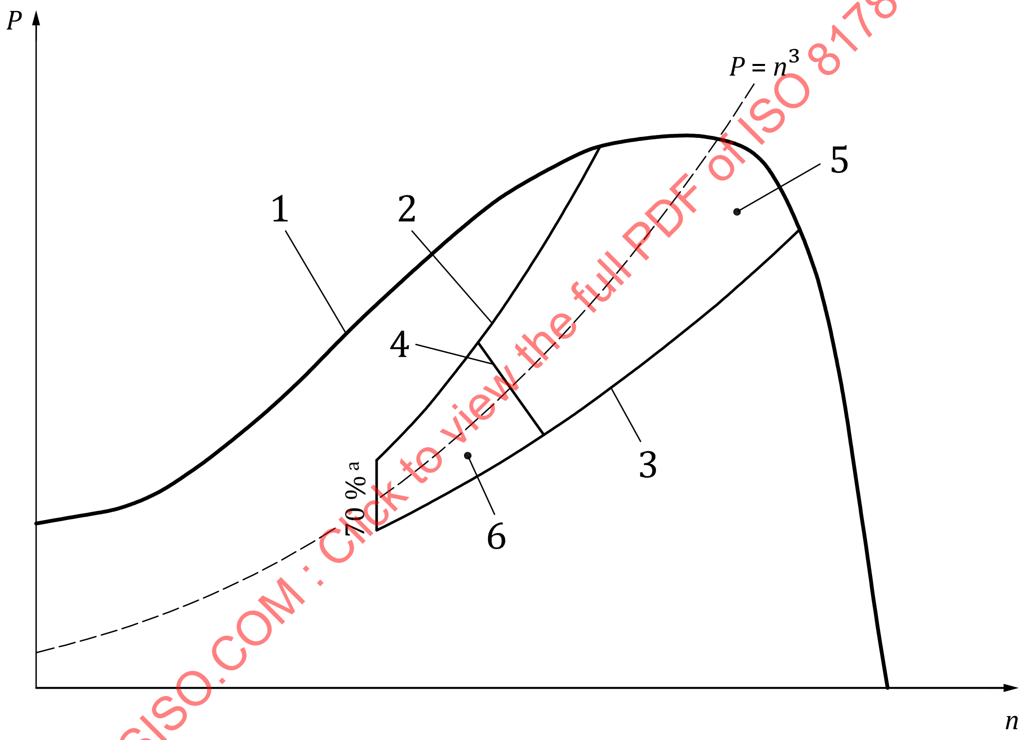
— $n_{100\%,\,rel}$: 84,6; $P_{max,\,rel}$ 46,1.

where

$P_{max,\,rel}$ is the percentage of the maximum net power;

$n_{100\%,\,rel}$ is the percentage of $n_{100\%}$

$n_{100\%}$ is the 100 % speed for the corresponding test cycle.



Key

n speed (%)

P power (% of maximum)

1 full load power curve

2 upper boundary curve

3 lower boundary curve

4 separating line between engine control area subzone 5 and subzone 6

5 engine control area subzone A

6 engine control area subzone B

a Lower speed limit of control area B (% of maximum speed).

Figure 9 — Engines tested to E3 test cycle

For E5 cycle marine engines with an individual cylinder displacement <5 l (see Figure 10):

a) Engine control area subzone A is defined by:

— upper boundary curve: $P_{max, rel} = 100 \times (n_{100\%, rel}/90)^{3,5}$;

— lower boundary curve: $P_{max, rel} = 70 \times (n_{100\%, rel}/100)^{2,5}$;

— upper power limit: full load power curve;

— lower limit of control area A: $3 \times (100\ \% - n_{100\%, rel})$.

b) Engine control area subzone B is defined by:

— lower speed limit: 0,7 ×n_(100 %);

— upper boundary curve: $P_{max, rel} = 100 \times (n_{100\%, rel}/90)^{3,5}$;

— lower boundary curve: $P_{max, rel} = 70 \times (n_{100\%, rel}/100)^{2,5}$.

c) Engine control area subzone C is defined by:

— upper boundary curve: $P_{max, rel} = 100 \times (n_{100\%, rel}/90)^{3,5}$;

— upper power limit: full load power curve;

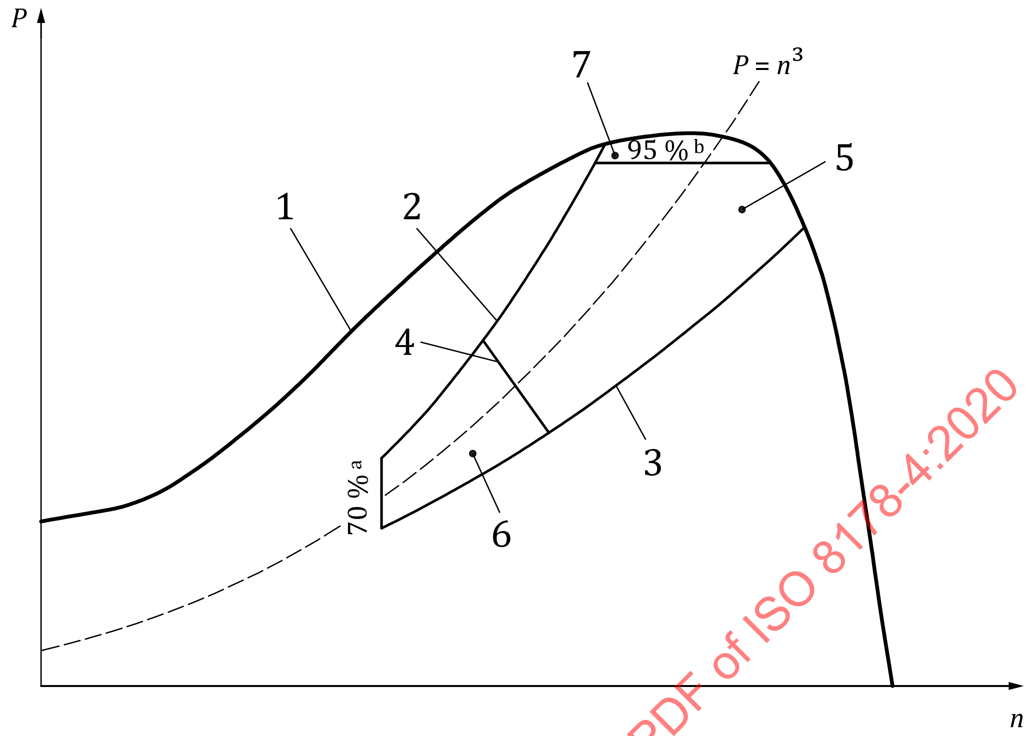
— upper speed limit: maximum speed permitted by governor;

— lower power limit of control area C: 95 % power at 88,7 % speed.

d) Line separating engine control area subzone A and B is defined by the following end-point coordinates:

— $n_{100\%, rel}$: 78,9; $P_{max, rel}$ 63,2;

— $n_{100\%, rel}$: 84,6; $P_{max, rel}$ 46,1;



Key

n speed (%)
P power (% of maximum)
1 upper power limit
2 upper boundary curve
3 lower boundary curve
4 lower limit of engine control area subzone A
5 engine control area subzone A
6 engine control area subzone B
7 engine control area subzone C
[a] Lower speed limit of engine control area subzone B (% of maximum speed).
[b] Lower power limit of engine control area subzone C (% of maximum power).

NOTE 1 *n* is expressed as a percentage of the rated speed; *P* is expressed as a percentage of the maximum power.

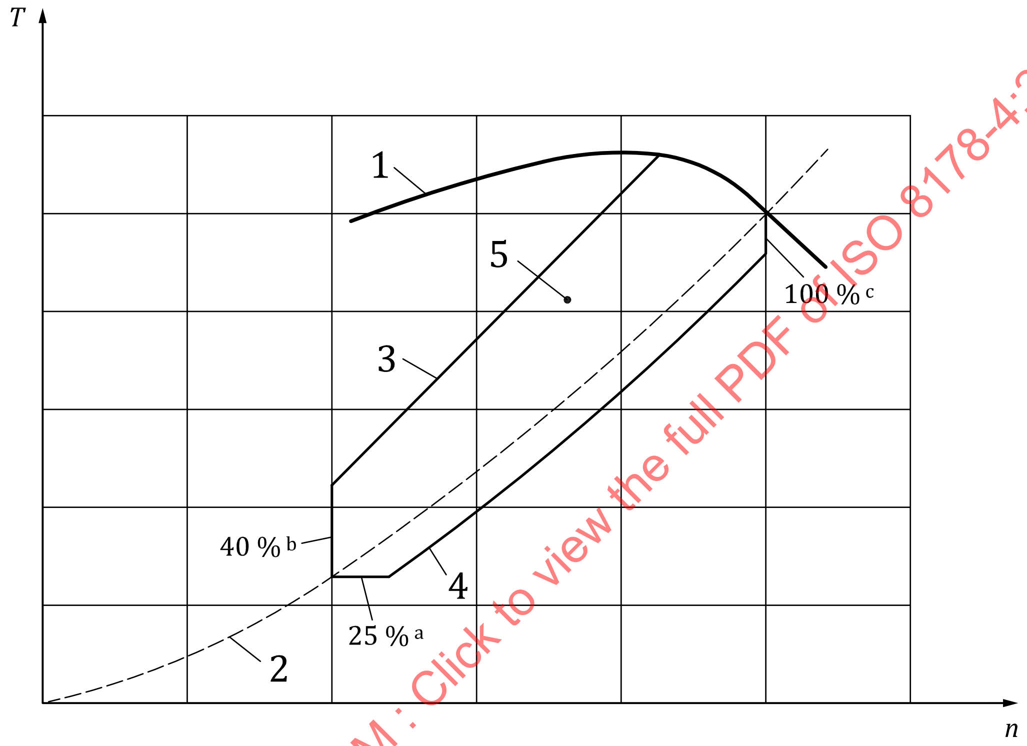
NOTE 2 Emission requirement for area A, B and C can be different. The limit for the entire area can be the same.

Figure 10 — Engines tested to E5 test cycle

10.5.2 Control area for engines tested to the E4 test cycle

These engines are mainly SI engines operated slightly above and below a propeller curve. The control area is related to the propeller curve and is defined as follows:

—	Lower speed limit:	$0,4 \times n_{100\%}$;
—	Lower torque limit:	$0,25 \times T_{max}$ at rated speed;
—	Upper propeller curve boundary:	$1,5\ n - 0,16\ n_{100\%,\ rel}$;
—	Lower propeller curve boundary:	$n^{1,5} - 0,08\ n_{100\%,\ rel}$.
—	Upper Torque limit:	Full load torque curve



Key

n	speed (%)		4	lower propeller curve boundary
T	torque (% of maximum)		5	engine control area
1	upper torque limit (full load torque curve)		a	Lower torque limit for engine control area (% of maximum torque at rated speed).
2	$n^{1,5}$ (propeller curve)		b	Lower speed limit for engine control area (% of rated speed).
3	upper propeller curve boundary		c	Upper speed limit for engine control area (% of rated speed).

NOTE n is expressed as a percentage of rated speed; T is expressed as a percentage of maximum rated torque.

Figure 11 — Engine tested to E4 test cycle

10.5.3 Control area for engines tested to the F cycle

These engines are mainly operated slightly above and below a cube law curve. The control area is related to the cube law curve and is defined as follows

— Lower speed limit: $0{,}63 \times n_{100\%}$;

— Lower power limit: $0{,}25 \times P_{max}$.

— Upper boundary curve: $P_{max,\ rel} = 115 \times (n_{100\%,\ rel}/100)^{2{,}5}$

— Lower boundary curve: $P_{max,\ rel} = 85 \times (n_{100\%,\ rel}/100)^{4}$

— Upper power limit: Full load power curve

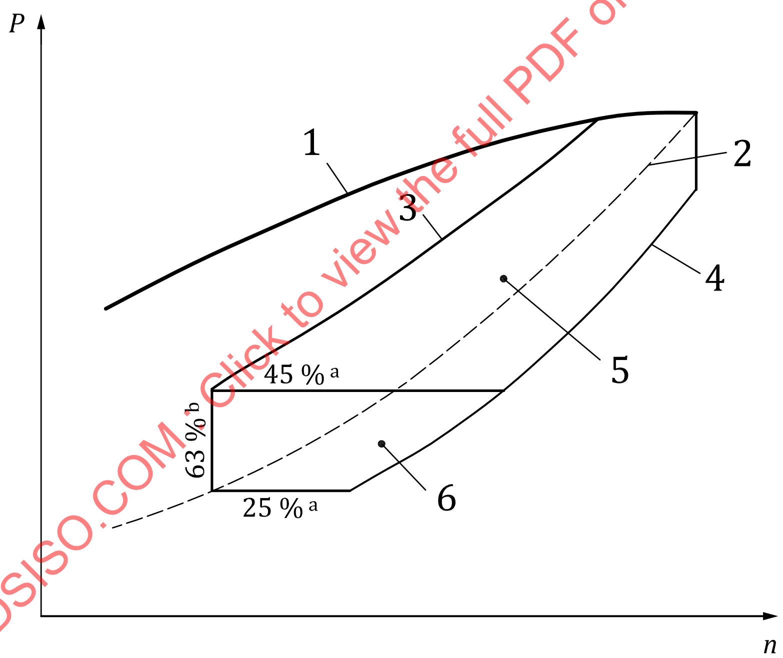
— Upper speed limit: Maximum speed permitted by governor

where

$P_{max,\ rel}$ is the percentage of the maximum net power (P_{max});

$n_{100\%,\ rel}$ is the percentage of $n_{100\%}$;

$n_{100\%}$ is the 100 % speed for the corresponding test cycle.



Key

n speed (%)
P power (% of maximum)
1 upper power limit (full load power curve)
2 cubic propeller curve
3 upper boundary curve
4 lower boundary curve
5 engine control area subzone A
6 engine control area subzone B
a Lower power limit (% of maximum power).
b Lower speed limit of control area B (% of maximum speed).

Figure 12 — Engines tested to the F cycle

Annex A
(normative)

Steady-state discrete-mode test-cycles

A.1 Test cycles type C “Non-road machinery and industrial equipment”

Table A.1 — Table of cycle C1 test modes and weighting factors

Mode number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Speed[a]	100 %				Intermediate			Idle
Torque[b] (%)	100	75	50	10	100	75	50	0
Weighting factor	0,15	0,15	0,15	0,1	0,1	0,1	0,1	0,15

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] The % torque is relative to the maximum torque at the commanded engine speed.

Table A.2 — Table of cycle C2 test modes and weighting factors

Mode number	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Speed[a]	100 %	Intermediate					Idle
Torque[b] (%)	25	100	75	50	25	10	0
Weighting factor	0,06	0,02	0,05	0,32	0,30	0,10	0,15

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] The % torque is relative to the maximum torque at the commanded engine speed.

A.2 Test cycles type D “Constant speed”

Table A.3 — Table of cycles type D test modes and weighting factors

Mode number (cycle D1)	**1**	**2**	**3**								
Speed[a]	100 %					Intermediate					Idle
Torque[b] (%)	100	75	50								
Weighting factor	0,3	0,5	0,2								
Mode number (cycle D2)	**1**	**2**	**3**	**4**	**5**						
Speed[a]	100 %					Intermediate					Idle
Torque[c] (%)	100	75	50	25	10						
Weighting factor	0,05	0,25	0,3	0,3	0,1						

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] The % torque is relative to the torque corresponding to the continuous rated power declared by the manufacturer as defined in ISO 8528-1.

[c] The % torque is relative to the torque corresponding to the rated power declared by the manufacturer as defined in ISO 8528-1.

A.3 Test cycles type E “Marine applications”

Table A.4 — Table of cycles type E test modes and weighting factors

<table>
<tr><td>Mode number (cycle E1)</td><td>1</td><td>2</td><td></td><td></td><td></td><td></td><td colspan="2">3</td><td>4</td><td colspan="2"></td><td></td><td>5</td></tr>
<tr><td>Speed[a]</td><td colspan="5">100 %</td><td colspan="7">Intermediate</td><td>Idle</td></tr>
<tr><td>Torque[b] (%)</td><td>100</td><td>75</td><td></td><td></td><td></td><td></td><td colspan="2">75</td><td>50</td><td colspan="2"></td><td></td><td>0</td></tr>
<tr><td>Weighting factor</td><td>0,08</td><td>0,11</td><td></td><td></td><td></td><td></td><td colspan="2">0,19</td><td>0,32</td><td colspan="2"></td><td></td><td>0,3</td></tr>
<tr><td>Mode number (cycle E2)</td><td>1</td><td>2</td><td>3</td><td>4</td><td></td><td></td><td colspan="2"></td><td></td><td colspan="2"></td><td></td><td></td></tr>
<tr><td>Speed[a]</td><td colspan="5">100 %</td><td colspan="7">Intermediate</td><td>Idle</td></tr>
<tr><td>Torque[d] (%)</td><td>100</td><td>75</td><td>50</td><td>25</td><td></td><td></td><td colspan="2"></td><td></td><td colspan="2"></td><td></td><td></td></tr>
<tr><td>Weighting factor</td><td>0,2</td><td>0,5</td><td>0,15</td><td>0,15</td><td></td><td></td><td colspan="2"></td><td></td><td colspan="2"></td><td></td><td></td></tr>
<tr><td>Mode number (cycle E3)</td><td colspan="5">1</td><td colspan="2">2</td><td colspan="3">3</td><td colspan="2">4</td><td></td></tr>
<tr><td>Speed[a] (%)</td><td colspan="5">100</td><td colspan="2">91</td><td colspan="3">80</td><td colspan="2">63</td><td></td></tr>
<tr><td>Power[c] (%)</td><td colspan="5">100</td><td colspan="2">75</td><td colspan="3">50</td><td colspan="2">25</td><td></td></tr>
<tr><td>Weighting factor</td><td colspan="5">0,2</td><td colspan="2">0,5</td><td colspan="3">0,15</td><td colspan="2">0,15</td><td></td></tr>
<tr><td>Mode number (cycle E4)</td><td colspan="5">1</td><td colspan="2">2</td><td colspan="3">3</td><td colspan="2">4</td><td>5</td></tr>
<tr><td>Speed[a] (%)</td><td colspan="5">100</td><td colspan="2">80</td><td colspan="3">60</td><td colspan="2">40</td><td>Idle</td></tr>
<tr><td>Torque[d] (%)</td><td colspan="5">100</td><td colspan="2">71,6</td><td colspan="3">46,5</td><td colspan="2">25,3</td><td>0</td></tr>
<tr><td>Weighting factor</td><td colspan="5">0,06</td><td colspan="2">0,14</td><td colspan="3">0,15</td><td colspan="2">0,25</td><td>0,40</td></tr>
<tr><td>Mode number (cycle E5)</td><td colspan="5">1</td><td colspan="2">2</td><td colspan="3">3</td><td colspan="2">4</td><td>5</td></tr>
<tr><td>Speed[a] (%)</td><td colspan="5">100</td><td colspan="2">91</td><td colspan="3">80</td><td colspan="2">63</td><td>Idle</td></tr>
<tr><td>Power[c] (%)</td><td colspan="5">100</td><td colspan="2">75</td><td colspan="3">50</td><td colspan="2">25</td><td>0</td></tr>
<tr><td>Weighting factor</td><td colspan="5">0,08</td><td colspan="2">0,13</td><td colspan="3">0,17</td><td colspan="2">0,32</td><td>0,3</td></tr>
</table>

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] Torque (%) is relative to the maximum torque at the commanded engine speed.

[c] Power (%) is relative to the maximum rated power at the 100 % speed.

[d] Torque (%) is relative to the torque corresponding to the rated net power declared by the manufacturer at the commanded engine speed.

A.4 Test cycle type F “Rail traction”

Table A.5 — Table of cycle type F test modes and weighting factors

Mode number	1	2[d]	3
Speed[a]	100 %	Intermediate	Idle
Power (%)	100[c]	50[c]	5[b]
Weighting factor	0,15	0,25	0,6

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] Power (%) at this mode is relative to the power at mode 1.

[c] Power (%) at this mode is relative to the maximum power at the commanded engine speed.

[d] For engines using a discrete control system (i.e. notch type controls) mode 2 is defined as an operation in the notch closest to mode 2 or 35 % of the rated power.

A.5 Test cycle type G "Utility, lawn & garden"

Table A.6 — Table of cycles type G test modes and weighting factors

Mode number (cycle G1)						**1**	**2**	**3**	**4**	**5**	**6**
Speed[a]	100 %					Intermediate					Idle
Torque[b] (%)						100	75	50	25	10	0
Weighting factor						0,09	0,20	0,29	0,30	0,07	0,05
Mode number (cycle G2)	**1**	**2**	**3**	**4**	**5**						**6**
Speed[a]	100 %					Intermediate					Idle
Torque[b] (%)	100	75	50	25	10						0
Weighting factor	0,09	0,20	0,29	0,30	0,07						0,05
Mode number (cycle G3)	**1**										**2**
Speed[a]	100 %					Intermediate					Idle
Torque[b] (%)	100										0
Weighting factor	0,85										0,15

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] Torque (%) is relative to the maximum torque at the commanded engine speed.

A.6 Test cycle type H "Snowmobile"

Table A.7 — Table of cycle type H test modes and weighting factors

Mode number	**1**	**2**	**3**	**4**	**5**
Speed[a] (%)	100	85	75	65	Idle
Torque[b] (%)	100	51	33	19	0
Weighting factor	0,12	0,27	0,25	0,31	0,05

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] Torque (%) is relative to the maximum torque at the commanded engine speed.

A.7 Test cycle type I "Transport refrigeration unit"

Table A.8 — Table of cycle type I test modes and weighting factors

Mode number	**1**	**2**	**3**	**4**
Speed[a] (%)	100 %		Intermediate	
Torque[b] (%)	75	50	75	50
Weighting factor	0,25	0,25	0,25	0,25

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] Torque (%) is relative to the maximum torque at the commanded engine speed.

A.8 Combined table of the weighting factors (for information only)

Table A.9 — Combined table of the weighting factors

Torque (%)[b]	**100**	**75**	**50**	**25**	**10**	**100**	**75**	**50**	**25**	**10**	**0**	**Table**
Speed[a]	100 %					Intermediate					Idle	
Non-road vehicles												
Cycle C1	0,15	0,15	0,15		0,1	0,1	0,1	0,1			0,15	A.1
Cycle C2				0,06		0,02	0,05	0,32	0,30	0,10	0,15	A.2
Constant speed												
Cycle D1	0,3	0,5	0,2									A.3
Cycle D2	0,05	0,25	0,3	0,3	0,1							
Utility, lawn and garden												
Cycle G1						0,09	0,2	0,29	0,3	0,07	0,05	A.6
Cycle G2	0,09	0,2	0,29	0,3	0,07						0,05	
Cycle G3	0,85										0,15	
Transport Refrigeration Unit												
Cycle I		0,25	0,25				0,25	0,25				A.8
Marine application												
Cycle E1	0,08	0,11					0,19	0,32			0,3	A.4
Cycle E2	0,2	0,5	0,15	0,15								
Marine application propeller law												
Mode number (Cycle E3)	**1**					**2**		**3**		**4**		A.4
Speed (%)[a]	100					91		80		63		
Power (%)[b]	100					75		50		25		
Weighting factor	0,2					0,5		0,15		0,15		
Mode number (Cycle E4)	**1**					**2**		**3**		**4**	**5**	
Speed (%)[a]	100					80		60		40	Idle	
Torque (%)[b]	100					71,6		46,5		25,3	0	
Weighting factor	0,06					0,14		0,15		0,25	0,40	
Mode number (Cycle E5)	**1**					**2**		**3**		**4**	**5**	
Speed (%)[a]	100					91		80		63	Idle	
Power (%)[b]	100					75		50		25	0	
Weighting factor	0,08					0,13		0,17		0,32	0,3	
Snowmobile												
Mode number (Cycle H)	**1**					**2**		**3**		**4**	**5**	A.7
Speed (%)[a]	100					85		75		65	Idle	
Torque (%)[b]	100					51		33		19	0	
Weighting factor	0,12					0,27		0,25		0,31	0,05	

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] See table of each individual cycle for details of what each torque (%) or power (%) figure represents.

Table A.9 *(continued)*

Torque (%)[b]	**100**	**75**	**50**	**25**	**10**	**100**	**75**	**50**	**25**	**10**	**0**	**Table**
Speed[a]	100 %					Intermediate					Idle	
Rail Traction												A.5
Mode number (Cycle F)	**1**					**2**					**3**	
Speed[a]	100 %					Intermediate					Idle	
Power (%)[b]	100					50					5	
Weighting factor	0,15					0,25					0,6	

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] See table of each individual cycle for details of what each torque (%) or power (%) figure represents.

Annex B
(normative)

Steady-state ramped-modal test cycles (RMCs)

B.1 Test cycles type C "Non-road machinery and industrial equipment"

Table B.1 — Table of RMC-C1 test modes

RMC Mode Number	Time in mode (s)	Engine speed[a,c]	Torque (%)[b,c]
1a Steady-state	126	Idle	0
1b Transition	20	Linear transition	Linear transition
2a Steady-state	159	Intermediate	100
2b Transition	20	Intermediate	Linear transition
3a Steady-state	160	Intermediate	50
3b Transition	20	Intermediate	Linear transition
4a Steady-state	162	Intermediate	75
4b Transition	20	Linear transition	Linear transition
5a Steady-state	246	100 %	100
5b Transition	20	100 %	Linear transition
6a Steady-state	164	100 %	10
6b Transition	20	100 %	Linear transition
7a Steady-state	248	100 %	75
7b Transition	20	100 %	Linear transition
8a Steady-state	247	100 %	50
8b Transition	20	Linear transition	Linear transition
9 Steady-state	128	Idle	0

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] Torque (%) is relative to the maximum torque at the commanded engine speed.

[c] Advance from one mode to the next within a 20-second transition phase. During the transition phase, command a linear progression from the torque setting of the current mode to the torque setting of the next mode, and simultaneously command a similar linear progression for engine speed if there is a change in speed setting.

Table B.2 — Table of RMC-C2 test modes

RMC Mode number	Time in mode (s)	Engine speed[a,c]	Torque (%)[b,c]
1a Steady-state	119	Idle	0
1b Transition	20	Linear transition	Linear transition
2a Steady-state	29	Intermediate	100
2b Transition	20	Intermediate	Linear transition

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] Torque (%) is relative to the maximum torque at the commanded engine speed.

[c] Advance from one mode to the next within a 20-second transition phase. During the transition phase, command a linear progression from the torque setting of the current mode to the torque setting of the next mode, and simultaneously command a similar linear progression for engine speed if there is a change in speed setting.

Table B.2 *(continued)*

RMC Mode number	Time in mode (s)	Engine speed[a,c]	Torque (%)[b,c]
3a Steady-state	150	Intermediate	10
3b Transition	20	Intermediate	Linear transition
4a Steady-state	80	Intermediate	75
4b Transition	20	Intermediate	Linear transition
5a Steady-state	513	Intermediate	25
5b Transition	20	Intermediate	Linear transition
6a Steady-state	549	Intermediate	50
6b Transition	20	Linear transition	Linear transition
7a Steady-state	96	100 %	25
7b Transition	20	Linear transition	Linear transition
8 Steady-state	124	Idle	0

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] Torque (%) is relative to the maximum torque at the commanded engine speed.

[c] Advance from one mode to the next within a 20-second transition phase. During the transition phase, command a linear progression from the torque setting of the current mode to the torque setting of the next mode, and simultaneously command a similar linear progression for engine speed if there is a change in speed setting.

B.2 Test cycles type D “Constant speed”

Table B.3 — Table of RMC-D2 test modes

RMC mode number	Time in mode (s)	Engine speed (%)[a]	Torque (%)[b,c]
1a Steady-state	53	100	100
1b Transition	20	100	Linear transition
2a Steady-state	101	100	10
2b Transition	20	100	Linear transition
3a Steady-state	277	100	75
3b Transition	20	100	Linear transition
4a Steady-state	339	100	25
4b Transition	20	100	Linear transition
5 Steady-state	350	100	50

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] Torque (%) is relative to the torque corresponding to the rated power declared by the manufacturer.

[c] Advance from one mode to the next within a 20-second transition phase. During the transition phase, command a linear progression from the torque setting of the current mode to the torque setting of the next mode.

B.3 Test cycles type E “Marine applications”

Table B.4 — Table of RMC-E2 test modes

RMC mode number	Time in mode (s)	Engine speed (%)[a]	Torque (%)[bc]
1a Steady-state	229	100	100
1b Transition	20	100	Linear transition
2a Steady-state	166	100	25
2b Transition	20	100	Linear transition
3a Steady-state	570	100	75
3b Transition	20	100	Linear transition
4 Steady-state	175	100	50

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] Torque (%) is relative to the maximum torque corresponding to the rated net power declared by the manufacturer at the commanded engine speed.

[c] Advance from one mode to the next within a 20-second transition phase. During the transition phase, command a linear progression from the torque setting of the current mode to the torque setting of the next mode.

Table B.5 — Table of RMC-E3 test modes

RMC mode number	Time in mode (s)	Engine speed (%)[a,c]	Power (%)[b,c]
1a Steady-state	229	100	100
1b Transition	20	Linear transition	Linear transition
2a Steady-state	166	63	25
2b Transition	20	Linear transition	Linear transition
3a Steady-state	570	91	75
3b Transition	20	Linear transition	Linear transition
4 Steady-state	175	80	50

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] Power (%) is relative to the maximum rated power at the 100 % speed.

[c] Advance from one mode to the next within a 20-second transition phase. During the transition phase, command a linear progression from the torque setting of the current mode to the torque setting of the next mode, and simultaneously command a similar linear progression for engine speed.

Table B.6 — Table of RMC-E5 test modes

RMC mode number	Time in mode (s)	Engine speed[a,c]	Power (%)[b,c]
1a Steady-state	167	Idle	0
1b Transition	20	Linear transition	Linear transition
2a Steady-state	85	100 %	100
2b Transition	20	Linear transition	Linear transition
3a Steady-state	354	63 %	25
3b Transition	20	Linear transition	Linear transition

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] Power (%) is relative to the maximum rated power at the 100 % speed.

[c] Advance from one mode to the next within a 20-second transition phase. During the transition phase, command a linear progression from the torque setting of the current mode to the torque setting of the next mode, and simultaneously command a similar linear progression for engine speed.

Table B.6 *(continued)*

RMC mode number	Time in mode (s)	Engine speed[a,c]	Power (%)[b,c]
4a Steady-state	141	91 %	75
4b Transition	20	Linear transition	Linear transition
5a Steady-state	182	80 %	50
5b Transition	20	Linear transition	Linear transition
6 Steady-state	171	Idle	0

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] Power (%) is relative to the maximum rated power at the 100 % speed.

[c] Advance from one mode to the next within a 20-second transition phase. During the transition phase, command a linear progression from the torque setting of the current mode to the torque setting of the next mode, and simultaneously command a similar linear progression for engine speed.

B.4 Test cycle type F "Rail traction"

Table B.7 — Table of RMC-F test modes

RMC Mode Number	Time in mode (s)	Engine speed[a,e]	Power (%)[e]
1a Steady-state	350	Idle	5[b]
1b Transition	20	Linear transition	Linear transition
2a Steady-state[d]	280	Intermediate	50[c]
2b Transition	20	Linear transition	Linear transition
3a Steady-state	160	100 %	100[c]
3b Transition	20	Linear Transition	Linear transition
4 Steady-state	350	Idle	5[c]

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] Power (%) at this mode is relative to the power at mode 3a.

[c] Power (%) at this mode is relative to the maximum power at the commanded engine speed.

[d] For engines using a discrete control system (i.e. notch type controls) mode 2a is defined as an operation in the notch closest to mode 2a or 35 % of the rated power.

[e] Advance from one mode to the next within a 20-second transition phase. During the transition phase, command a linear progression from the torque setting of the current mode to the torque setting of the next mode, and simultaneously command a similar linear progression for engine speed if there is a change in speed setting.

B.5 Test cycles type G "Utility, lawn & garden"

Table B.8 — Table of RMC-G1 test modes

RMC mode number	Time in mode (s)	Engine speed[a,c]	Torque (%)[b,c]
1a Steady-state	41	Idle	0
1b Transition	20	Linear transition	Linear transition
2a Steady-state	135	Intermediate	100

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] Torque (%) is relative to the maximum torque at the commanded engine speed.

[c] Advance from one mode to the next within a 20-second transition phase. During the transition phase, command a linear progression from the torque setting of the current mode to the torque setting of the next mode and simultaneously command a similar linear progression for engine speed if there is a change in speed setting.

Table B.8 *(continued)*

RMC mode number	Time in mode (s)	Engine speed[a,c]	Torque (%)[b,c]
2b Transition	20	Intermediate	Linear transition
3a Steady-state	112	Intermediate	10
3b Transition	20	Intermediate	Linear transition
4a Steady-state	337	Intermediate	75
4b Transition	20	Intermediate	Linear transition
5a Steady-state	518	Intermediate	25
5b Transition	20	Intermediate	Linear transition
6a Steady-state	494	Intermediate	50
6b Transition	20	Linear transition	Linear transition
7 Steady-state	43	Idle	0

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] Torque (%) is relative to the maximum torque at the commanded engine speed.

[c] Advance from one mode to the next within a 20-second transition phase. During the transition phase, command a linear progression from the torque setting of the current mode to the torque setting of the next mode and simultaneously command a similar linear progression for engine speed if there is a change in speed setting.

Table B.9 — Table of RMC-G2 test modes

RMC mode number	Time in mode (s)	Engine speed[a,c]	Torque (%)[b,c]
1a Steady-state	41	Idle	0
1b Transition	20	Linear transition	Linear transition
2a Steady-state	135	100 %	100
2b Transition	20	100 %	Linear transition
3a Steady-state	112	100 %	10
3b Transition	20	100 %	Linear transition
4a Steady-state	337	100 %	75
4b Transition	20	100 %	Linear transition
5a Steady-state	518	100 %	25
5b Transition	20	100 %	Linear transition
6a Steady-state	494	100 %	50
6b Transition	20	Linear transition	Linear transition
7 Steady-state	43	Idle	0

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] Torque (%) is relative to the maximum torque at the commanded engine speed.

[c] Advance from one mode to the next within a 20-second transition phase. During the transition phase, command a linear progression from the torque setting of the current mode to the torque setting of the next mode and simultaneously command a similar linear progression for engine speed if there is a change in speed setting.

B.6 Test cycle type H "Snowmobile"

Table B.10 — Table of RMC-H test modes

RMC mode number	Time in mode (s)	Engine speed[a,c]	Torque (%)[b,c]
1a Steady-state	27	Idle	0
1b Transition	20	Linear transition	Linear transition
2a Steady-state	121	100 %	100
2b Transition	20	Linear transition	Linear transition
3a Steady-state	347	65 %	19
3b Transition	20	Linear transition	Linear transition
4a Steady-state	305	85 %	51
4b Transition	20	Linear transition	Linear transition
5a Steady-state	272	75 %	33
5b Transition	20	Linear transition	Linear transition
6 Steady-state	28	Idle	0

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] Torque (%) is relative to the maximum torque at the commanded engine speed.

[c] Advance from one mode to the next within a 20-second transition phase. During the transition phase, command a linear progression from the torque setting of the current mode to the torque setting of the next mode, and simultaneously command a similar linear progression for engine speed if there is a change in speed setting.

B.7 Test cycle type I "Transport refrigeration unit"

Table B.11 — Table of RMC-I test modes

RMC mode number	Time in mode (s)	Engine speed[a,c]	Torque (%)[b,c]
1a Steady-state	290	Intermediate	75
1b Transition	20	Intermediate	Linear transition
2a Steady-state	280	Intermediate	50
2b Transition	20	Linear transition	Linear transition
3a Steady-state	280	100 %	75
3b Transition	20	100 %	Linear transition
4 Steady-state	290	100 %	50

[a] See 7.2, 7.4 and 7.7 for determination of required test speeds.

[b] Torque (%) is relative to the maximum torque at the commanded engine speed.

[c] Advance from one mode to the next within a 20-second transition phase. During the transition phase, command a linear progression from the torque setting of the current mode to the torque setting of the next mode, and simultaneously command a similar linear progression for engine speed if there is a change in speed setting.

Annex C
(normative)

Transient test cycles

C.1 General

Table C.1 and C.2 shall be used in the manner described in Clauses 7, 8 and 9 or Annex H.

C.2 NRTC engine dynamometer schedule

Table C.1

Time (s)	Normalized speed (%)	Normalized torque (%)
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	0	0
11	0	0
12	0	0
13	0	0
14	0	0
15	0	0
16	0	0
17	0	0
18	0	0
19	0	0
20	0	0
21	0	0
22	0	0
23	0	0
24	1	3
25	1	3
26	1	3
27	1	3
28	1	3
29	1	3
30	1	6

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
31	1	6
32	2	1
33	4	13
34	7	18
35	9	21
36	17	20
37	33	42
38	57	46
39	44	33
40	31	0
41	22	27
42	33	43
43	80	49
44	105	47
45	98	70
46	104	36
47	104	65
48	96	71
49	101	62
50	102	51
51	102	50
52	102	46
53	102	41
54	102	31
55	89	2
56	82	0
57	47	1
58	23	1
59	1	3
60	1	8
61	1	3
62	1	5
63	1	6
64	1	4
65	1	4
66	0	6
67	1	4
68	9	21
69	25	56
70	64	26
71	60	31
72	63	20
73	62	24

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
74	64	8
75	58	44
76	65	10
77	65	12
78	68	23
79	69	30
80	71	30
81	74	15
82	71	23
83	73	20
84	73	21
85	73	19
86	70	33
87	70	34
88	65	47
89	66	47
90	64	53
91	65	45
92	66	38
93	67	49
94	69	39
95	69	39
96	66	42
97	71	29
98	75	29
99	72	23
100	74	22
101	75	24
102	73	30
103	74	24
104	77	6
105	76	12
106	74	39
107	72	30
108	75	22
109	78	64
110	102	34
111	103	28
112	103	28
113	103	19
114	103	32
115	104	25
116	103	38

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
117	103	39
118	103	34
119	102	44
120	103	38
121	102	43
122	103	34
123	102	41
124	103	44
125	103	37
126	103	27
127	104	13
128	104	30
129	104	19
130	103	28
131	104	40
132	104	32
133	101	63
134	102	54
135	102	52
136	102	51
137	103	40
138	104	34
139	102	36
140	104	44
141	103	44
142	104	33
143	102	27
144	103	26
145	79	53
146	51	37
147	24	23
148	13	33
149	19	55
150	45	30
151	34	7
152	14	4
153	8	16
154	15	6
155	39	47
156	39	4
157	35	26
158	27	38
159	43	40

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
160	14	23
161	10	10
162	15	33
163	35	72
164	60	39
165	55	31
166	47	30
167	16	7
168	0	6
169	0	8
170	0	8
171	0	2
172	2	17
173	10	28
174	28	31
175	33	30
176	36	0
177	19	10
178	1	18
179	0	16
180	1	3
181	1	4
182	1	5
183	1	6
184	1	5
185	1	3
186	1	4
187	1	4
188	1	6
189	8	18
190	20	51
191	49	19
192	41	13
193	31	16
194	28	21
195	21	17
196	31	21
197	21	8
198	0	14
199	0	12
200	3	8
201	3	22
202	12	20

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
203	14	20
204	16	17
205	20	18
206	27	34
207	32	33
208	41	31
209	43	31
210	37	33
211	26	18
212	18	29
213	14	51
214	13	11
215	12	9
216	15	33
217	20	25
218	25	17
219	31	29
220	36	66
221	66	40
222	50	13
223	16	24
224	26	50
225	64	23
226	81	20
227	83	11
228	79	23
229	76	31
230	68	24
231	59	33
232	59	3
233	25	7
234	21	10
235	20	19
236	4	10
237	5	7
238	4	5
239	4	6
240	4	6
241	4	5
242	7	5
243	16	28
244	28	25
245	52	53

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
246	50	8
247	26	40
248	48	29
249	54	39
250	60	42
251	48	18
252	54	51
253	88	90
254	103	84
255	103	85
256	102	84
257	58	66
258	64	97
259	56	80
260	51	67
261	52	96
262	63	62
263	71	6
264	33	16
265	47	45
266	43	56
267	42	27
268	42	64
269	75	74
270	68	96
271	86	61
272	66	0
273	37	0
274	45	37
275	68	96
276	80	97
277	92	96
278	90	97
279	82	96
280	94	81
281	90	85
282	96	65
283	70	96
284	55	95
285	70	96
286	79	96
287	81	71
288	71	60

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
289	92	65
290	82	63
291	61	47
292	52	37
293	24	0
294	20	7
295	39	48
296	39	54
297	63	58
298	53	31
299	51	24
300	48	40
301	39	0
302	35	18
303	36	16
304	29	17
305	28	21
306	31	15
307	31	10
308	43	19
309	49	63
310	78	61
311	78	46
312	66	65
313	78	97
314	84	63
315	57	26
316	36	22
317	20	34
318	19	8
319	9	10
320	5	5
321	7	11
322	15	15
323	12	9
324	13	27
325	15	28
326	16	28
327	16	31
328	15	20
329	17	0
330	20	34
331	21	25

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
332	20	0
333	23	25
334	30	58
335	63	96
336	83	60
337	61	0
338	26	0
339	29	44
340	68	97
341	80	97
342	88	97
343	99	88
344	102	86
345	100	82
346	74	79
347	57	79
348	76	97
349	84	97
350	86	97
351	81	98
352	83	83
353	65	96
354	93	72
355	63	60
356	72	49
357	56	27
358	29	0
359	18	13
360	25	11
361	28	24
362	34	53
363	65	83
364	80	44
365	77	46
366	76	50
367	45	52
368	61	98
369	61	69
370	63	49
371	32	0
372	10	8
373	17	7
374	16	13

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
375	11	6
376	9	5
377	9	12
378	12	46
379	15	30
380	26	28
381	13	9
382	16	21
383	24	4
384	36	43
385	65	85
386	78	66
387	63	39
388	32	34
389	46	55
390	47	42
391	42	39
392	27	0
393	14	5
394	14	14
395	24	54
396	60	90
397	53	66
398	70	48
399	77	93
400	79	67
401	46	65
402	69	98
403	80	97
404	74	97
405	75	98
406	56	61
407	42	0
408	36	32
409	34	43
410	68	83
411	102	48
412	62	0
413	41	39
414	71	86
415	91	52
416	89	55
417	89	56

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
418	88	58
419	78	69
420	98	39
421	64	61
422	90	34
423	88	38
424	97	62
425	100	53
426	81	58
427	74	51
428	76	57
429	76	72
430	85	72
431	84	60
432	83	72
433	83	72
434	86	72
435	89	72
436	86	72
437	87	72
438	88	72
439	88	71
440	87	72
441	85	71
442	88	72
443	88	72
444	84	72
445	83	73
446	77	73
447	74	73
448	76	72
449	46	77
450	78	62
451	79	35
452	82	38
453	81	41
454	79	37
455	78	35
456	78	38
457	78	46
458	75	49
459	73	50
460	79	58

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
461	79	71
462	83	44
463	53	48
464	40	48
465	51	75
466	75	72
467	89	67
468	93	60
469	89	73
470	86	73
471	81	73
472	78	73
473	78	73
474	76	73
475	79	73
476	82	73
477	86	73
478	88	72
479	92	71
480	97	54
481	73	43
482	36	64
483	63	31
484	78	1
485	69	27
486	67	28
487	72	9
488	71	9
489	78	36
490	81	56
491	75	53
492	60	45
493	50	37
494	66	41
495	51	61
496	68	47
497	29	42
498	24	73
499	64	71
500	90	71
501	100	61
502	94	73
503	84	73

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
504	79	73
505	75	72
506	78	73
507	80	73
508	81	73
509	81	73
510	83	73
511	85	73
512	84	73
513	85	73
514	86	73
515	85	73
516	85	73
517	85	72
518	85	73
519	83	73
520	79	73
521	78	73
522	81	73
523	82	72
524	94	56
525	66	48
526	35	71
527	51	44
528	60	23
529	64	10
530	63	14
531	70	37
532	76	45
533	78	18
534	76	51
535	75	33
536	81	17
537	76	45
538	76	30
539	80	14
540	71	18
541	71	14
542	71	11
543	65	2
544	31	26
545	24	72
546	64	70

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
547	77	62
548	80	68
549	83	53
550	83	50
551	83	50
552	85	43
553	86	45
554	89	35
555	82	61
556	87	50
557	85	55
558	89	49
559	87	70
560	91	39
561	72	3
562	43	25
563	30	60
564	40	45
565	37	32
566	37	32
567	43	70
568	70	54
569	77	47
570	79	66
571	85	53
572	83	57
573	86	52
574	85	51
575	70	39
576	50	5
577	38	36
578	30	71
579	75	53
580	84	40
581	85	42
582	86	49
583	86	57
584	89	68
585	99	61
586	77	29
587	81	72
588	89	69
589	49	56

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
590	79	70
591	104	59
592	103	54
593	102	56
594	102	56
595	103	61
596	102	64
597	103	60
598	93	72
599	86	73
600	76	73
601	59	49
602	46	22
603	40	65
604	72	31
605	72	27
606	67	44
607	68	37
608	67	42
609	68	50
610	77	43
611	58	4
612	22	37
613	57	69
614	68	38
615	73	2
616	40	14
617	42	38
618	64	69
619	64	74
620	67	73
621	65	73
622	68	73
623	65	49
624	81	0
625	37	25
626	24	69
627	68	71
628	70	71
629	76	70
630	71	72
631	73	69
632	76	70

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
633	77	72
634	77	72
635	77	72
636	77	70
637	76	71
638	76	71
639	77	71
640	77	71
641	78	70
642	77	70
643	77	71
644	79	72
645	78	70
646	80	70
647	82	71
648	84	71
649	83	71
650	83	73
651	81	70
652	80	71
653	78	71
654	76	70
655	76	70
656	76	71
657	79	71
658	78	71
659	81	70
660	83	72
661	84	71
662	86	71
663	87	71
664	92	72
665	91	72
666	90	71
667	90	71
668	91	71
669	90	70
670	90	72
671	91	71
672	90	71
673	90	71
674	92	72
675	93	69

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
676	90	70
677	93	72
678	91	70
679	89	71
680	91	71
681	90	71
682	90	71
683	92	71
684	91	71
685	93	71
686	93	68
687	98	68
688	98	67
689	100	69
690	99	68
691	100	71
692	99	68
693	100	69
694	102	72
695	101	69
696	100	69
697	102	71
698	102	71
699	102	69
700	102	71
701	102	68
702	100	69
703	102	70
704	102	68
705	102	70
706	102	72
707	102	68
708	102	69
709	100	68
710	102	71
711	101	64
712	102	69
713	102	69
714	101	69
715	102	64
716	102	69
717	102	68
718	102	70

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
719	102	69
720	102	70
721	102	70
722	102	62
723	104	38
724	104	15
725	102	24
726	102	45
727	102	47
728	104	40
729	101	52
730	103	32
731	102	50
732	103	30
733	103	44
734	102	40
735	103	43
736	103	41
737	102	46
738	103	39
739	102	41
740	103	41
741	102	38
742	103	39
743	102	46
744	104	46
745	103	49
746	102	45
747	103	42
748	103	46
749	103	38
750	102	48
751	103	35
752	102	48
753	103	49
754	102	48
755	102	46
756	103	47
757	102	49
758	102	42
759	102	52
760	102	57
761	102	55

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
762	102	61
763	102	61
764	102	58
765	103	58
766	102	59
767	102	54
768	102	63
769	102	61
770	103	55
771	102	60
772	102	72
773	103	56
774	102	55
775	102	67
776	103	56
777	84	42
778	48	7
779	48	6
780	48	6
781	48	7
782	48	6
783	48	7
784	67	21
785	105	59
786	105	96
787	105	74
788	105	66
789	105	62
790	105	66
791	89	41
792	52	5
793	48	5
794	48	7
795	48	5
796	48	6
797	48	4
798	52	6
799	51	5
800	51	6
801	51	6
802	52	5
803	52	5
804	57	44

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
805	98	90
806	105	94
807	105	100
808	105	98
809	105	95
810	105	96
811	105	92
812	104	97
813	100	85
814	94	74
815	87	62
816	81	50
817	81	46
818	80	39
819	80	32
820	81	28
821	80	26
822	80	23
823	80	23
824	80	20
825	81	19
826	80	18
827	81	17
828	80	20
829	81	24
830	81	21
831	80	26
832	80	24
833	80	23
834	80	22
835	81	21
836	81	24
837	81	24
838	81	22
839	81	22
840	81	21
841	81	31
842	81	27
843	80	26
844	80	26
845	81	25
846	80	21
847	81	20

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
848	83	21
849	83	15
850	83	12
851	83	9
852	83	8
853	83	7
854	83	6
855	83	6
856	83	6
857	83	6
858	83	6
859	76	5
860	49	8
861	51	7
862	51	20
863	78	52
864	80	38
865	81	33
866	83	29
867	83	22
868	83	16
869	83	12
870	83	9
871	83	8
872	83	7
873	83	6
874	83	6
875	83	6
876	83	6
877	83	6
878	59	4
879	50	5
880	51	5
881	51	5
882	51	5
883	50	5
884	50	5
885	50	5
886	50	5
887	50	5
888	51	5
889	51	5
890	51	5

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
891	63	50
892	81	34
893	81	25
894	81	29
895	81	23
896	80	24
897	81	24
898	81	28
899	81	27
900	81	22
901	81	19
902	81	17
903	81	17
904	81	17
905	81	15
906	80	15
907	80	28
908	81	22
909	81	24
910	81	19
911	81	21
912	81	20
913	83	26
914	80	63
915	80	59
916	83	100
917	81	73
918	83	53
919	80	76
920	81	61
921	80	50
922	81	37
923	82	49
924	83	37
925	83	25
926	83	17
927	83	13
928	83	10
929	83	8
930	83	7
931	83	7
932	83	6
933	83	6

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
934	83	6
935	71	5
936	49	24
937	69	64
938	81	50
939	81	43
940	81	42
941	81	31
942	81	30
943	81	35
944	81	28
945	81	27
946	80	27
947	81	31
948	81	41
949	81	41
950	81	37
951	81	43
952	81	34
953	81	31
954	81	26
955	81	23
956	81	27
957	81	38
958	81	40
959	81	39
960	81	27
961	81	33
962	80	28
963	81	34
964	83	72
965	81	49
966	81	51
967	80	55
968	81	48
969	81	36
970	81	39
971	81	38
972	80	41
973	81	30
974	81	23
975	81	19
976	81	25

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
977	81	29
978	83	47
979	81	90
980	81	75
981	80	60
982	81	48
983	81	41
984	81	30
985	80	24
986	81	20
987	81	21
988	81	29
989	81	29
990	81	27
991	81	23
992	81	25
993	81	26
994	81	22
995	81	20
996	81	17
997	81	23
998	83	65
999	81	54
1 000	81	50
1 001	81	41
1 002	81	35
1 003	81	37
1 004	81	29
1 005	81	28
1 006	81	24
1 007	81	19
1 008	81	16
1 009	80	16
1 010	83	23
1 011	83	17
1 012	83	13
1 013	83	27
1 014	81	58
1 015	81	60
1 016	81	46
1 017	80	41
1 018	80	36
1 019	81	26

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
1 020	86	18
1 021	82	35
1 022	79	53
1 023	82	30
1 024	83	29
1 025	83	32
1 026	83	28
1 027	76	60
1 028	79	51
1 029	86	26
1 030	82	34
1 031	84	25
1 032	86	23
1 033	85	22
1 034	83	26
1 035	83	25
1 036	83	37
1 037	84	14
1 038	83	39
1 039	76	70
1 040	78	81
1 041	75	71
1 042	86	47
1 043	83	35
1 044	81	43
1 045	81	41
1 046	79	46
1 047	80	44
1 048	84	20
1 049	79	31
1 050	87	29
1 051	82	49
1 052	84	21
1 053	82	56
1 054	81	30
1 055	85	21
1 056	86	16
1 057	79	52
1 058	78	60
1 059	74	55
1 060	78	84
1 061	80	54
1 062	80	35

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
1 063	82	24
1 064	83	43
1 065	79	49
1 066	83	50
1 067	86	12
1 068	64	14
1 069	24	14
1 070	49	21
1 071	77	48
1 072	103	11
1 073	98	48
1 074	101	34
1 075	99	39
1 076	103	11
1 077	103	19
1 078	103	7
1 079	103	13
1 080	103	10
1 081	102	13
1 082	101	29
1 083	102	25
1 084	102	20
1 085	96	60
1 086	99	38
1 087	102	24
1 088	100	31
1 089	100	28
1 090	98	3
1 091	102	26
1 092	95	64
1 093	102	23
1 094	102	25
1 095	98	42
1 096	93	68
1 097	101	25
1 098	95	64
1 099	101	35
1 100	94	59
1 101	97	37
1 102	97	60
1 103	93	98
1 104	98	53
1 105	103	13

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
1 106	103	11
1 107	103	11
1 108	103	13
1 109	103	10
1 110	103	10
1 111	103	11
1 112	103	10
1 113	103	10
1 114	102	18
1 115	102	31
1 116	101	24
1 117	102	19
1 118	103	10
1 119	102	12
1 120	99	56
1 121	96	59
1 122	74	28
1 123	66	62
1 124	74	29
1 125	64	74
1 126	69	40
1 127	76	2
1 128	72	29
1 129	66	65
1 130	54	69
1 131	69	56
1 132	69	40
1 133	73	54
1 134	63	92
1 135	61	67
1 136	72	42
1 137	78	2
1 138	76	34
1 139	67	80
1 140	70	67
1 141	53	70
1 142	72	65
1 143	60	57
1 144	74	29
1 145	69	31
1 146	76	1
1 147	74	22
1 148	72	52

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
1 149	62	96
1 150	54	72
1 151	72	28
1 152	72	35
1 153	64	68
1 154	74	27
1 155	76	14
1 156	69	38
1 157	66	59
1 158	64	99
1 159	51	86
1 160	70	53
1 161	72	36
1 162	71	47
1 163	70	42
1 164	67	34
1 165	74	2
1 166	75	21
1 167	74	15
1 168	75	13
1 169	76	10
1 170	75	13
1 171	75	10
1 172	75	7
1 173	75	13
1 174	76	8
1 175	76	7
1 176	67	45
1 177	75	13
1 178	75	12
1 179	73	21
1 180	68	46
1 181	74	8
1 182	76	11
1 183	76	14
1 184	74	11
1 185	74	18
1 186	73	22
1 187	74	20
1 188	74	19
1 189	70	22
1 190	71	23
1 191	73	19

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
1 192	73	19
1 193	72	20
1 194	64	60
1 195	70	39
1 196	66	56
1 197	68	64
1 198	30	68
1 199	70	38
1 200	66	47
1 201	76	14
1 202	74	18
1 203	69	46
1 204	68	62
1 205	68	62
1 206	68	62
1 207	68	62
1 208	68	62
1 209	68	62
1 210	54	50
1 211	41	37
1 212	27	25
1 213	14	12
1 214	0	0
1 215	0	0
1 216	0	0
1 217	0	0
1 218	0	0
1 219	0	0
1 220	0	0
1 221	0	0
1 222	0	0
1 223	0	0
1 224	0	0
1 225	0	0
1 226	0	0
1 227	0	0
1 228	0	0
1 229	0	0
1 230	0	0
1 231	0	0
1 232	0	0
1 233	0	0
1 234	0	0

Table C.1 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
1 235	0	0
1 236	0	0
1 237	0	0
1 238	0	0

C.3 LSI-NRTC engine dynamometer schedule

Table C.2

Time (s)	Normalized speed (%)	Normalized torque (%)
0	0	0
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	1	8
10	6	54
11	8	61
12	34	59
13	22	46
14	5	51
15	18	51
16	31	50
17	30	56
18	31	49
19	25	66
20	58	55
21	43	31
22	16	45
23	24	38
24	24	27
25	30	33
26	45	65
27	50	49
28	23	42
29	13	42
30	9	45
31	23	30
32	37	45

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
33	44	50
34	49	52
35	55	49
36	61	46
37	66	38
38	42	33
39	17	41
40	17	37
41	7	50
42	20	32
43	5	55
44	30	42
45	44	53
46	45	56
47	41	52
48	24	41
49	15	40
50	11	44
51	32	31
52	38	54
53	38	47
54	9	55
55	10	50
56	33	55
57	48	56
58	49	47
59	33	44
60	52	43
61	55	43
62	59	38
63	44	28
64	24	37
65	12	44
66	9	47
67	12	52
68	34	21
69	29	44
70	44	54
71	54	62
72	62	57
73	72	56
74	88	71
75	100	69

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
76	100	34
77	100	42
78	100	54
79	100	58
80	100	38
81	83	17
82	61	15
83	43	22
84	24	35
85	16	39
86	15	45
87	32	34
88	14	42
89	8	48
90	5	51
91	10	41
92	12	37
93	4	47
94	3	49
95	3	50
96	4	49
97	4	48
98	8	43
99	2	51
100	5	46
101	8	41
102	4	47
103	3	49
104	6	45
105	3	48
106	10	42
107	18	27
108	3	50
109	11	41
110	34	29
111	51	57
112	67	63
113	61	32
114	44	31
115	48	54
116	69	65
117	85	65
118	81	29

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
119	74	21
120	62	23
121	76	58
122	96	75
123	100	77
124	100	27
125	100	79
126	100	79
127	100	81
128	100	57
129	99	52
130	81	35
131	69	29
132	47	22
133	34	28
134	27	37
135	83	60
136	100	74
137	100	7
138	100	2
139	70	18
140	23	39
141	5	54
142	11	40
143	11	34
144	11	41
145	19	25
146	16	32
147	20	31
148	21	38
149	21	42
150	9	51
151	4	49
152	2	51
153	1	58
154	21	57
155	29	47
156	33	45
157	16	49
158	38	45
159	37	43
160	35	42
161	39	43

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
162	51	49
163	59	55
164	65	54
165	76	62
166	84	59
167	83	29
168	67	35
169	84	54
170	90	58
171	93	43
172	90	29
173	66	19
174	52	16
175	49	17
176	56	38
177	73	71
178	86	80
179	96	75
180	89	27
181	66	17
182	50	18
183	36	25
184	36	24
185	38	40
186	40	50
187	27	48
188	19	48
189	23	50
190	19	45
191	6	51
192	24	48
193	49	67
194	47	49
195	22	44
196	25	40
197	38	54
198	43	55
199	40	52
200	14	49
201	11	45
202	7	48
203	26	41
204	41	59

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
205	53	60
206	44	54
207	22	40
208	24	41
209	32	53
210	44	74
211	57	25
212	22	49
213	29	45
214	19	37
215	14	43
216	36	40
217	43	63
218	42	49
219	15	50
220	19	44
221	47	59
222	67	80
223	76	74
224	87	66
225	98	61
226	100	38
227	97	27
228	100	53
229	100	72
230	100	49
231	100	4
232	100	13
233	87	15
234	53	26
235	33	27
236	39	19
237	51	33
238	67	54
239	83	60
240	95	52
241	100	50
242	100	36
243	100	25
244	85	16
245	62	16
246	40	26
247	56	39

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
248	81	75
249	98	86
250	100	76
251	100	51
252	100	78
253	100	83
254	100	100
255	100	66
256	100	85
257	100	72
258	100	45
259	98	58
260	60	30
261	43	32
262	71	36
263	44	32
264	24	38
265	42	17
266	22	51
267	13	53
268	23	45
269	29	50
270	28	42
271	21	55
272	34	57
273	44	47
274	19	46
275	13	44
276	25	36
277	43	51
278	55	73
279	68	72
280	76	63
281	80	45
282	83	40
283	78	26
284	60	20
285	47	19
286	52	25
287	36	30
288	40	26
289	45	34
290	47	35

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
291	42	28
292	46	38
293	48	44
294	68	61
295	70	47
296	48	28
297	42	22
298	31	29
299	22	35
300	28	28
301	46	46
302	62	69
303	76	81
304	88	85
305	98	81
306	100	74
307	100	13
308	100	11
309	100	17
310	99	3
311	80	7
312	62	11
313	63	11
314	64	16
315	69	43
316	81	67
317	93	74
318	100	72
319	94	27
320	73	15
321	40	33
322	40	52
323	50	50
324	11	53
325	12	45
326	5	50
327	1	55
328	7	55
329	62	60
330	80	28
331	23	37
332	39	58
333	47	24

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
334	59	51
335	58	68
336	36	52
337	18	42
338	36	52
339	59	73
340	72	85
341	85	92
342	99	90
343	100	72
344	100	18
345	100	76
346	100	64
347	100	87
348	100	97
349	100	84
350	100	100
351	100	91
352	100	83
353	100	93
354	100	100
355	94	43
356	72	10
357	77	3
358	48	2
359	29	5
360	59	19
361	63	5
362	35	2
363	24	3
364	28	2
365	36	16
366	54	23
367	60	10
368	33	1
369	23	0
370	16	0
371	11	0
372	20	0
373	25	2
374	40	3
375	33	4
376	34	5

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
377	46	7
378	57	10
379	66	11
380	75	14
381	79	11
382	80	16
383	92	21
384	99	16
385	83	2
386	71	2
387	69	4
388	67	4
389	74	16
390	86	25
391	97	28
392	100	15
393	83	2
394	62	4
395	40	6
396	49	10
397	36	5
398	27	4
399	29	3
400	22	2
401	13	3
402	37	36
403	90	26
404	41	2
405	25	2
406	29	2
407	38	7
408	50	13
409	55	10
410	29	3
411	24	7
412	51	16
413	62	15
414	72	35
415	91	74
416	100	73
417	100	8
418	98	11
419	100	59

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
420	100	98
421	100	99
422	100	75
423	100	95
424	100	100
425	100	97
426	100	90
427	100	86
428	100	82
429	97	43
430	70	16
431	50	20
432	42	33
433	89	64
434	89	77
435	99	95
436	100	41
437	77	12
438	29	37
439	16	41
440	16	38
441	15	36
442	18	44
443	4	55
444	24	26
445	26	35
446	15	45
447	21	39
448	29	52
449	26	46
450	27	50
451	13	43
452	25	36
453	37	57
454	29	46
455	17	39
456	13	41
457	19	38
458	28	35
459	8	51
460	14	36
461	17	47
462	34	39

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
463	34	57
464	11	70
465	13	51
466	13	68
467	38	44
468	53	67
469	29	69
470	19	65
471	52	45
472	61	79
473	29	70
474	15	53
475	15	60
476	52	40
477	50	61
478	13	74
479	46	51
480	60	73
481	33	84
482	31	63
483	41	42
484	26	69
485	23	65
486	48	49
487	28	57
488	16	67
489	39	48
490	47	73
491	35	87
492	26	73
493	30	61
494	34	49
495	35	66
496	56	47
497	49	64
498	59	64
499	42	69
500	6	77
501	5	59
502	17	59
503	45	53
504	21	62
505	31	60

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
506	53	68
507	48	79
508	45	61
509	51	47
510	41	48
511	26	58
512	21	62
513	50	52
514	39	65
515	23	65
516	42	62
517	57	80
518	66	81
519	64	62
520	45	42
521	33	42
522	27	57
523	31	59
524	41	53
525	45	72
526	48	73
527	46	90
528	56	76
529	64	76
530	69	64
531	72	59
532	73	58
533	71	56
534	66	48
535	61	50
536	55	56
537	52	52
538	54	49
539	61	50
540	64	54
541	67	54
542	68	52
543	60	53
544	52	50
545	45	49
546	38	45
547	32	45
548	26	53

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
549	23	56
550	30	49
551	33	55
552	35	59
553	33	65
554	30	67
555	28	59
556	25	58
557	23	56
558	22	57
559	19	63
560	14	63
561	31	61
562	35	62
563	21	80
564	28	65
565	7	74
566	23	54
567	38	54
568	14	78
569	38	58
570	52	75
571	59	81
572	66	69
573	54	44
574	48	34
575	44	33
576	40	40
577	28	58
578	27	63
579	35	45
580	20	66
581	15	60
582	10	52
583	22	56
584	30	62
585	21	67
586	29	53
587	41	56
588	15	67
589	24	56
590	42	69
591	39	83

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
592	40	73
593	35	67
594	32	61
595	30	65
596	30	72
597	48	51
598	66	58
599	62	71
600	36	63
601	17	59
602	16	50
603	16	62
604	34	48
605	51	66
606	35	74
607	15	56
608	19	54
609	43	65
610	52	80
611	52	83
612	49	57
613	48	46
614	37	36
615	25	44
616	14	53
617	13	64
618	23	56
619	21	63
620	18	67
621	20	54
622	16	67
623	26	56
624	41	65
625	28	62
626	19	60
627	33	56
628	37	70
629	24	79
630	28	57
631	40	57
632	40	58
633	28	44
634	25	41

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
635	29	53
636	31	55
637	26	64
638	20	50
639	16	53
640	11	54
641	13	53
642	23	50
643	32	59
644	36	63
645	33	59
646	24	52
647	20	52
648	22	55
649	30	53
650	37	59
651	41	58
652	36	54
653	29	49
654	24	53
655	14	57
656	10	54
657	9	55
658	10	57
659	13	55
660	15	64
661	31	57
662	19	69
663	14	59
664	33	57
665	41	65
666	39	64
667	39	59
668	39	51
669	28	41
670	19	49
671	27	54
672	37	63
673	32	74
674	16	70
675	12	67
676	13	60
677	17	56

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
678	15	62
679	25	47
680	27	64
681	14	71
682	5	65
683	6	57
684	6	57
685	15	52
686	22	61
687	14	77
688	12	67
689	12	62
690	14	59
691	15	58
692	18	55
693	22	53
694	19	69
695	14	67
696	9	63
697	8	56
698	17	49
699	25	55
700	14	70
701	12	60
702	22	57
703	27	67
704	29	68
705	34	62
706	35	61
707	28	78
708	11	71
709	4	58
710	5	58
711	10	56
712	20	63
713	13	76
714	11	65
715	9	60
716	7	55
717	8	53
718	10	60
719	28	53
720	12	73

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
721	4	64
722	4	61
723	4	61
724	10	56
725	8	61
726	20	56
727	32	62
728	33	66
729	34	73
730	31	61
731	33	55
732	33	60
733	31	59
734	29	58
735	31	53
736	33	51
737	33	48
738	27	44
739	21	52
740	13	57
741	12	56
742	10	64
743	22	47
744	15	74
745	8	66
746	34	47
747	18	71
748	9	57
749	11	55
750	12	57
751	10	61
752	16	53
753	12	75
754	6	70
755	12	55
756	24	50
757	28	60
758	28	64
759	23	60
760	20	56
761	26	50
762	28	55
763	18	56

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
764	15	52
765	11	59
766	16	59
767	34	54
768	16	82
769	15	64
770	36	53
771	45	64
772	41	59
773	34	50
774	27	45
775	22	52
776	18	55
777	26	54
778	39	62
779	37	71
780	32	58
781	24	48
782	14	59
783	7	59
784	7	55
785	18	49
786	40	62
787	44	73
788	41	68
789	35	48
790	29	54
791	22	69
792	46	53
793	59	71
794	69	68
795	75	47
796	62	32
797	48	35
798	27	59
799	13	58
800	14	54
801	21	53
802	23	56
803	23	57
804	23	65
805	13	65
806	9	64

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
807	27	56
808	26	78
809	40	61
810	35	76
811	28	66
812	23	57
813	16	50
814	11	53
815	9	57
816	9	62
817	27	57
818	42	69
819	47	75
820	53	67
821	61	62
822	63	53
823	60	54
824	56	44
825	49	39
826	39	35
827	30	34
828	33	46
829	44	56
830	50	56
831	44	52
832	38	46
833	33	44
834	29	45
835	24	46
836	18	52
837	9	55
838	10	54
839	20	53
840	27	58
841	29	59
842	30	62
843	30	65
844	27	66
845	32	58
846	40	56
847	41	57
848	18	73
849	15	55

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
850	18	50
851	17	52
852	20	49
853	16	62
854	4	67
855	2	64
856	7	54
857	10	50
858	9	57
859	5	62
860	12	51
861	14	65
862	9	64
863	31	50
864	30	78
865	21	65
866	14	51
867	10	55
868	6	59
869	7	59
870	19	54
871	23	61
872	24	62
873	34	61
874	51	67
875	60	66
876	58	55
877	60	52
878	64	55
879	68	51
880	63	54
881	64	50
882	68	58
883	73	47
884	63	40
885	50	38
886	29	61
887	14	61
888	14	53
889	42	6
890	58	6
891	58	6
892	77	39

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
893	93	56
894	93	44
895	93	37
896	93	31
897	93	25
898	93	26
899	93	27
900	93	25
901	93	21
902	93	22
903	93	24
904	93	23
905	93	27
906	93	34
907	93	32
908	93	26
909	93	31
910	93	34
911	93	31
912	93	33
913	93	36
914	93	37
915	93	34
916	93	30
917	93	32
918	93	35
919	93	35
920	93	32
921	93	28
922	93	23
923	94	18
924	95	18
925	96	17
926	95	13
927	96	10
928	95	9
929	95	7
930	95	7
931	96	7
932	96	6
933	96	6
934	95	6
935	90	6

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
936	69	43
937	76	62
938	93	47
939	93	39
940	93	35
941	93	34
942	93	36
943	93	39
944	93	34
945	93	26
946	93	23
947	93	24
948	93	24
949	93	22
950	93	19
951	93	17
952	93	19
953	93	22
954	93	24
955	93	23
956	93	20
957	93	20
958	94	19
959	95	19
960	95	17
961	96	13
962	95	10
963	96	9
964	95	7
965	95	7
966	95	7
967	95	6
968	96	6
969	96	6
970	89	6
971	68	6
972	57	6
973	66	32
974	84	52
975	93	46
976	93	42
977	93	36
978	93	28

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
979	93	23
980	93	19
981	93	16
982	93	15
983	93	16
984	93	15
985	93	14
986	93	15
987	93	16
988	94	15
989	93	32
990	93	45
991	93	43
992	93	37
993	93	29
994	93	23
995	93	20
996	93	18
997	93	16
998	93	17
999	93	16
1 000	93	15
1 001	93	15
1 002	93	15
1 003	93	14
1 004	93	15
1 005	93	15
1 006	93	14
1 007	93	13
1 008	93	14
1 009	93	14
1 010	93	15
1 011	93	16
1 012	93	17
1 013	93	20
1 014	93	22
1 015	93	20
1 016	93	19
1 017	93	20
1 018	93	19
1 019	93	19
1 020	93	20
1 021	93	32

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
1 022	93	37
1 023	93	28
1 024	93	26
1 025	93	24
1 026	93	22
1 027	93	22
1 028	93	21
1 029	93	20
1 030	93	20
1 031	93	20
1 032	93	20
1 033	93	19
1 034	93	18
1 035	93	20
1 036	93	20
1 037	93	20
1 038	93	20
1 039	93	19
1 040	93	18
1 041	93	18
1 042	93	17
1 043	93	16
1 044	93	16
1 045	93	15
1 046	93	16
1 047	93	18
1 048	93	37
1 049	93	48
1 050	93	38
1 051	93	31
1 052	93	26
1 053	93	21
1 054	93	18
1 055	93	16
1 056	93	17
1 057	93	18
1 058	93	19
1 059	93	21
1 060	93	20
1 061	93	18
1 062	93	17
1 063	93	17
1 064	93	18

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
1 065	93	18
1 066	93	18
1 067	93	19
1 068	93	18
1 069	93	18
1 070	93	20
1 071	93	23
1 072	93	25
1 073	93	25
1 074	93	24
1 075	93	24
1 076	93	22
1 077	93	22
1 078	93	22
1 079	93	19
1 080	93	16
1 081	95	17
1 082	95	37
1 083	93	43
1 084	93	32
1 085	93	27
1 086	93	26
1 087	93	24
1 088	93	22
1 089	93	22
1 090	93	22
1 091	93	23
1 092	93	22
1 093	93	22
1 094	93	23
1 095	93	23
1 096	93	23
1 097	93	22
1 098	93	23
1 099	93	23
1 100	93	23
1 101	93	25
1 102	93	27
1 103	93	26
1 104	93	25
1 105	93	27
1 106	93	27
1 107	93	27

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
1 108	93	24
1 109	93	20
1 110	93	18
1 111	93	17
1 112	93	17
1 113	93	18
1 114	93	18
1 115	93	18
1 116	93	19
1 117	93	22
1 118	93	22
1 119	93	19
1 120	93	17
1 121	93	17
1 122	93	18
1 123	93	18
1 124	93	19
1 125	93	19
1 126	93	20
1 127	93	19
1 128	93	20
1 129	93	25
1 130	93	30
1 131	93	31
1 132	93	26
1 133	93	21
1 134	93	18
1 135	93	20
1 136	93	25
1 137	93	24
1 138	93	21
1 139	93	21
1 140	93	22
1 141	93	22
1 142	93	28
1 143	93	29
1 144	93	23
1 145	93	21
1 146	93	18
1 147	93	16
1 148	93	16
1 149	93	16
1 150	93	17

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
1 151	93	17
1 152	93	17
1 153	93	17
1 154	93	23
1 155	93	26
1 156	93	22
1 157	93	18
1 158	93	16
1 159	93	16
1 160	93	17
1 161	93	19
1 162	93	18
1 163	93	16
1 164	93	19
1 165	93	22
1 166	93	25
1 167	93	29
1 168	93	27
1 169	93	22
1 170	93	18
1 171	93	16
1 172	93	19
1 173	93	19
1 174	93	17
1 175	93	17
1 176	93	17
1 177	93	16
1 178	93	16
1 179	93	15
1 180	93	16
1 181	93	15
1 182	93	17
1 183	93	21
1 184	93	30
1 185	93	53
1 186	93	54
1 187	93	38
1 188	93	30
1 189	93	24
1 190	93	20
1 191	95	20
1 192	96	18
1 193	96	15

Table C.2 *(continued)*

Time (s)	Normalized speed (%)	Normalized torque (%)
1 194	96	11
1 195	95	9
1 196	95	8
1 197	96	7
1 198	94	33
1 199	93	46
1 200	93	37
1 201	16	8
1 202	0	0
1 203	0	0
1 204	0	0
1 205	0	0
1 206	0	0
1 207	0	0
1 208	0	0
1 209	0	0

Annex D
(informative)

Calculation of the exhaust gas mass flow and/or of the combustion air mass flow

NOTE Formulae in the annex are not converted to SI-symbols.

D.1 General

This annex may be applied using good engineering judgement.

The formulae given in this annex are for stoichiometric calculations and for the calculation of the exhaust gas mass flow from the exhaust composition and the fuel composition.

All dimensions relating to volumes are defined for standard conditions: 0 °C, 101,32 kPa.

In this annex the same symbols are used as in the main part of this document.

The concentration units used are %volume for the components CO_2, O_2, H_2O and N_2 and µmol/mol for all others.

Symbols and abbreviations (additionally to those explained in the main part of this document) used in this annex are given in Table D.1.

Table D.1 — Symbols and abbreviated terms

Symbol	Term	Unit
q_v	Volume flow	m^3/h
q_{vew}	Volume flow of wet exhaust	m^3/h
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_{mgas}	Emission of component M_{GAS}	g/h
w_{ox}	Oxygen content of dry intake air	% mass
w_{inert}	Inert gas content of dry intake air	% mass

D.2 Stoichiometric calculations for the burning of fuel; fuel specific factors

D.2.1 Basic data for stoichiometric calculations

In the formulae of this annex as far as possible the basic data relative atomic mass, molar mass and molar volume are used. Concrete numbers for these data were mostly used only in final formulae. This has the advantage, that the derivation of the formulae can be understood more easily. Also the fact, that these data can be slightly different, depending on the used data handbook, can be best met by general and not concrete formulations. The concrete numbers given in Table D.2 were used for basic data.

Table D.2 — Relative atomic masses, molar masses and molar volumes

Description	Symbol	Number	Unit
Relative atomic mass of hydrogen	A_{rH}	1,007 94	g/mol
Relative atomic mass of carbon	A_{rC}	12,011	g/mol
Relative atomic mass of sulfur	A_{rS}	32,065	g/mol
Relative atomic mass of nitrogen	A_{rN}	14,006 7	g/mol
Relative atomic mass of oxygen	A_{rO}	15,999 4	g/mol
Molar mass of water	M_{rH2O}	18,015 34	g/mol
Molar mass of carbon dioxide	M_{rCO2}	44,01	g/mol
Molar mass of carbon monoxide	M_{rCO}	28,011	g/mol
Molar mass of oxygen	M_{rO2}	31,998 8	g/mol
Molar mass of nitrogen	M_{rN2}	28,011	g/mol
Molar mass of nitric oxide	M_{rNO}	30,008	g/mol
Molar mass of nitrogen dioxide	M_{rNO2}	46,01	g/mol
Molar mass of sulfur dioxide	M_{rSO2}	64,066	g/mol
Molar volume of water	V_{mH2O}	22,401	l/mol
Molar volume of carbon dioxide	V_{mCO2}	22,262	l/mol
Molar volume of carbon monoxide	V_{mCO}	22,408	l/mol
Molar volume of oxygen	V_{mO2}	22,392	l/mol
Molar volume of nitrogen	V_{mN2}	22,390	l/mol
Molar volume of nitric oxide	V_{mNO}	22,391	l/mol
Molar volume of nitrogen dioxide	V_{mNO2}	21,809	l/mol
Molar volume of sulfur dioxide	V_{mSO2}	21,891	l/mol

Assuming no compressibility effects, all of the gases involved in the engine intake/combustion/exhaust process can be considered to be ideal and the volumetric calculations given hereafter are based on that assumption. Hence according to Avogadro's Hypothesis, they each occupy 22,414 l/mol (see Table D.3).

NOTE The molar volume of gases is a function of interactions of the molecules at collisions. The collision of ideal gas molecules are only physical impacts, while real gas molecules interact additionally by Van-der-Waals forces at the moment of the collision. This effect reduces the molar volume of real gases. In mixtures also collisions between more ideal gases and more real gases occur; these collisions have a more ideal character. In the case of exhaust emissions the almost perfect ideal gas nitrogen has by far the highest concentration and therefore only very few collisions between real gas molecules occur.

Table D.3 — Molar volumes used in this document

Molar volume of water	V_{mH2O}	22,401	l/mol
Molar volume of carbon dioxide	V_{mCO2}	22,262	l/mol
Molar volume of carbon monoxide	V_{mCO}	22,400	l/mol
Molar volume of oxygen	V_{mO2}	22,392	l/mol
Molar volume of nitrogen	V_{mN2}	22,403	l/mol
Molar volume of nitric oxide	V_{mNO}	21,809	l/mol
Molar volume of nitrogen dioxide	V_{mNO2}	21,809	l/mol
Molar volume of sulfur dioxide	V_{mSO2}	21,890	l/mol

For the stoichiometry of combustion the following composition of the dry intake air is assumed:

— concentration of inert gases

w_{inert} = 76,8 % mass, 79,0 % volume

NOTE Included in the inert gases is CO_2 with 0,061 % mass, 0,04 % volume.

— concentration of oxygen

w_{ox} = 23,2 % mass, 21,0 % volume.

D.2.2 General formulae

D.2.2.1 Formulae related to the components

Calculation of mass concentration c_{mgas} from volumetric concentration c_{vgas} of component:

$$c_{mgas} = c_{vgas} \times \rho_{gas} \tag{D.1}$$

with ρ_{gas} = gas density of the component in [kg/m^3], c_{vgas} in [µmol/mol] and c_{mgas} in [mg/m^3]

The gas density ρ_{gas} can be calculated from the basic data molecular mass $M_{r,\,gas}$ and molar volume V_{mgas}:

$$c_{mgas} = c_{vgas} \times \rho_{gas} \tag{D.2}$$

with ρ_{gas} in [kg/m^3], M_{rgas} in [g/mol] and V_{mgas} in [l/mol]

D.2.2.2 Formulae related to the fuel

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 molecule is used, because the real carbon atom number 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):

$$\alpha = \frac{\frac{w_H}{A_{r_H}}}{\frac{w_C}{A_{r_C}}} = 11{,}916\,4 \times \frac{w_H}{w_C} \tag{D.3}$$

$$\beta = \frac{\frac{w_C}{A_{r_C}}}{\frac{w_C}{A_{r_C}}} = 1 \tag{D.4}$$

$$\gamma = \frac{\frac{w_S}{A_{r_S}}}{\frac{w_C}{A_{r_C}}} = 0{,}374\,64 \times \frac{w_S}{w_C} \tag{D.5}$$

$$\delta = \frac{\frac{w_N}{A_{r_N}}}{\frac{w_C}{A_{r_C}}} = 0,857\,52 \times \frac{w_N}{w_C} \tag{D.6}$$

$$\varepsilon = \frac{\frac{w_O}{A_{r_O}}}{\frac{w_C}{A_{r_C}}} = 0,750\,72 \times \frac{w_O}{w_C} \tag{D.7}$$

$$w_H = \frac{\alpha \times A_{r_H} \times 100}{M_{r_f}} \tag{D.8}$$

$$w_C = \frac{\beta \times A_{r_C} \times 100}{M_{r_f}} \tag{D.9}$$

$$w_S = \frac{\gamma \times A_{r_S} \times 100}{M_{r_f}} \tag{D.10}$$

$$w_N = \frac{\delta \times A_{r_N} \times 100}{M_{r_f}} \tag{D.11}$$

$$w_O = \frac{\varepsilon \times A_{r_O} \times 100}{M_{r_f}} \tag{D.12}$$

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

$$M_{rf} = \alpha \times A_{r_H} + \beta \times A_{r_C} + \gamma \times A_{r_S} + \delta \times A_{r_N} + \varepsilon \times A_{r_O} \tag{D.13}$$

D.2.2.3 Formulae related to the saturation vapour pressure

Calculation of the saturation vapour pressure p_a [Pa] as a function of the temperature t [K] according to the Federal Register:

$$\begin{aligned} p_a = \exp(&-12,150\,799 \times \ln(t) - 8\,499,22 \times t^{-2} - 7\,423,186\,5 \times t^{-1} \\ &+ 96,163\,514\,7 + 0,024\,917\,646 \times t - 1,316\,011\,9 \times 10^{-5} \times t^2 \\ &- 1,146\,045\,4 \times 10^{-8} \times t^3 + 2,170\,128\,9 \times 10^{-11} \times t^4 \\ &- 3,610\,258 \times 10^{-15} \times t^5 + 3,850\,451\,9 \times 10^{-18} \times t^6 - 1,431\,7 \\ &\times 10^{-21} \times t^7 \end{aligned} \tag{D.14}$$

The following simpler formula leads to equivalent results:

$$\begin{aligned} p_a = (&4,856\,884 + 0,266\,088\,9 \times (t - 273,15) + 0,016\,889\,19 \times (t - 273,15)^2 \\ &- 7,477\,123 \times 10^{-5} \times (t - 273,15)^3 + 8,105\,25 \times 10^{-6} \\ &\times (t - 273,15)^4 - 3,115\,221 \times 10^{-8} \times (t - 273,15)^5) \times \frac{1\,013,2}{760} \\ &\times 100 \end{aligned} \tag{D.15}$$

D.2.2.4 Formulae related to the soot concentration

Correlations for the calculation of the **soot concentration** c_{Cw} [mg/m^3 in wet exhaust] shall be provided by the manufacturer of the measurement device.

D.2.3 Reaction formulae and formulae for the stoichiometric burning of fuel

D.2.3.1 General

In this clause the stoichiometry of the combustion of fuels containing H, C, S, N and O is described. The relations of masses of the reaction partners are calculated and the standard volumes for gaseous compounds. For each combusted element the resulting additional volume (exhaust volume – air volume) is given. The summation of these additional volumes results in the total additional volume f_{fw}.

On this basis formulae for further exhaust relevant data are derived (conversion factor wet/dry, stoichiometric air demand and fuel specific factor f_{fd}).

D.2.3.2 Combustion of hydrogen

$$\mathrm{H(f)} + {}^1\!/_4\,\mathrm{O_2(a)} \rightarrow {}^1\!/_2\,\mathrm{H_2O(e)}$$

$$1\ \mathrm{kg\ H} + M_{\mathrm{r_{O2}}} \Big/ \left(4 \times A_{\mathrm{r_H}}\right) [\mathrm{kg\ O_2}] \ \rightarrow\ M_{\mathrm{r_{H2O}}} \Big/ \left(2 \times A_{\mathrm{r_H}}\right) [\mathrm{kg\ H_2O}] \qquad \text{masses}$$

$$V_{\mathrm{m_{O2}}} \Big/ \left(4 \times A_{\mathrm{r_H}}\right) \left[\mathrm{m^3\ O_2}\right] \ \rightarrow\ V_{\mathrm{m_{H2O}}} \Big/ \left(2 \times A_{\mathrm{r_H}}\right) \left[\mathrm{m^3\ H_2O}\right] \qquad \text{volumes}$$

Additional volume by combustion:

$$\left(2 \times V_{\mathrm{mH2O}} - V_{\mathrm{mO2}}\right) / \left(4 \times A_{\mathrm{rH}}\right) = (2 \times 22{,}414 - 22{,}414) / (4 \times 1{,}007\ 94) = 5{,}559\ 4 \left[\mathrm{m^3 / kg\ H}\right]$$

D.2.3.3 Combustion of carbon

$$C(\mathrm{f}) + O_2(\mathrm{a}) \rightarrow CO_2(\mathrm{e})$$

$$1\mathrm{kg\ C} + M_{\mathrm{rO2}} / A_{\mathrm{rC}} [\mathrm{kg\ O_2}] \rightarrow M_{\mathrm{rCO2}} / A_{\mathrm{rC}} [\mathrm{kg\ CO_2}] \qquad \text{masses}$$

$$V_{\mathrm{mo2}} / A_{\mathrm{rC}} \left[\mathrm{m^3 O_2}\right] \rightarrow V_{\mathrm{mCO2}} / A_{\mathrm{r}} C \left[\mathrm{m^3 CO_2}\right] \qquad \text{volumes}$$

Additional volume by combustion:

$$\left(V_{\mathrm{mCO2}} - V_{\mathrm{mO2}}\right) / A_{\mathrm{rC}} = (22{,}414 - 22{,}414) / 12{,}011 = 0 \left[\mathrm{m^3 / kg\ C}\right]$$

D.2.3.4 Combustion of sulfur

$$\mathrm{S(f)} + \mathrm{O_2(a)} \rightarrow \mathrm{SO_2(e)}$$

$$1\mathrm{kg\ S} + M_{\mathrm{r_{O2}}} / A_{\mathrm{r_S}} [\mathrm{kg\ O_2}] \rightarrow M_{\mathrm{r_{SO2}}} / A_{\mathrm{r_S}} [\mathrm{kg\ SO_2}] \qquad \text{masses}$$

$\left(V_{m_{SO2}} - V_{m_{O2}}\right)/A_{r_S} = (22{,}414 - 22{,}414)/32{,}065 = 0\ m^3/\text{kg S}$ volumes

Additional volume by combustion:

$\left(V_{m_{SO2}} - V_{m_{O2}}\right)/A_{r_S} = (21{,}891 - 22{,}392)/32{,}065 - 0{,}0156\ 2\ m^3/\text{kg S}$

D.2.3.5 Reaction of nitrogen

$\text{N(f)} \rightarrow \text{N}_2\text{(e)}$

$1\ \text{kg N} \rightarrow 1\ \text{kg N}_2$ masses

$1 \rightarrow V_{\text{mN2}}/M_{\text{rN2}}\ \left[\text{m}^3\text{N}_2\right]$ volumes

Additional volume by combustion:

$V_{\text{mN2}}/M_{\text{rN2}} = 22{,}414/28{,}01 = 0{,}800\ 21\ \text{m}^3/\text{kg N}$

D.2.3.6 Consideration of the fuel oxygen

Since the combustion of the other fuel elements with the above given formulae was calculated with consumption of air oxygen, the fuel oxygen is not needed for combustion and can therefore be considered to be set free as gaseous molecular oxygen in the exhaust:

$\text{O(f)} \rightarrow \text{O}_2\text{(e)}$

$1\ \text{kg O} \rightarrow 1\ \text{kg O}_2$ masses

$V_{m_{O2}}/M_{r_{O2}}\ \left[\text{m}^3\text{O}_2\right]$ volumes

Additional volume by combustion:

$V_{m_{O2}}/M_{r_{O2}} = 22{,}414/31{,}998\ 8 = 0{,}700\ 46\ \text{m}^3/\text{kg}$

D.2.3.7 Total additional volume f_{fw} [m³/kg fuel]

The fuel specific constants f_{fw} [m³ volume change from combustion air to wet exhaust/kg fuel] and the corresponding value f_{fd} for the dry exhaust are further used to calculate the dry to wet correction factor and the exhaust densities (see D.2.4 and D.2.5). f_{fw} can be calculated by adding up the additional volumes of the combustion of the fuel elements given in D.2.3.2 to D.2.3.6:

$$f_{\text{fw}} = 0{,}055\ 594 \times w_{\text{H}} + 0{,}008\ 002\ 1 \times w_{\text{N}} + 0{,}007\ 004\ 6 \times w_{\text{O}} \quad \text{(D.16)}$$

For the calculation of the exhaust volume flow V_{ew} it can be used as follows:

$$q_{V_{\text{ew}}} = q_{V_{\text{aw}}} + q_{\text{mf}} \times f_{\text{fw}} \quad \text{(D.17)}$$

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

D.2.3.8 Calculation of the factor f_{fd} from f_{fw}

The factor f_{fd} can be used for the calculation of the dry exhaust volume flow as follows:

$$q_{V_{ed}} = q_{V_{ad}} + f_{fd} \times q_{mf} \tag{D.18}$$

f_{fd} values are always negative, that means that the volume of dry exhaust is always less than the volume of the intake air.

Based on Formula (D.18) the following derivations can be made:

$$f_{fd} = \frac{q_{V_{ed}} - q_{V_{ad}}}{q_{mf}} \tag{D.19}$$

The volume of moisture due to combustion which must be removed from the total volume change due to combustion ($q_{mf} \times f_{fw}$) is given by:

$$\frac{w_H \times q_{mf} \times V_{m_{H2O}}}{100 \times 2 \times A_{r_H}}$$

$$f_{fd} = \frac{q_{V_{ad}} + q_{mf} \times f_{fw} - \dfrac{w_H \times q_{mf} \times V_{m_{H2O}}}{100 \times 2 \times A_{r_H}} - q_{Vad}}{q_{mf}} \tag{D.20}$$

$$f_{fd} = f_{fw} - \frac{w_H \times V_{m_{H2O}}}{200 \times A_{r_H}} = f_{fw} - w_H \times 0{,}111\,18 \tag{D.21}$$

$$f_{fd} = -0{,}055\,586 \times w_H + 0{,}008\,002 \times w_N + 0{,}007\,004\,6 \times w_O \tag{D.22}$$

D.2.3.9 Stoichiometric air demand A/F_{st}

With the reactions of the fuel elements given in D.2.3.2 to D.2.3.6 the stoichiometric air demand (= mass of air needed for combustion of 1 kg fuel) can be given as follows:

$$A/F_{st} = \left(\frac{w_C}{A_{r_C}} + \frac{w_H}{4 \times A_{r_H}} + \frac{w_S}{A_{r_S}} - \frac{w_O}{2 \times A_{r_O}} \right) \times \frac{M_{r_{O2}}}{w_{ox}} \tag{D.23}$$

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

In concrete numbers:

$$A/F_{st} = \left(\frac{w_C}{12{,}011} + \frac{w_H}{4{,}031\,76} + \frac{w_S}{32{,}06} - \frac{w_O}{31{,}998\,8} \right) \times 1{,}382 \tag{D.24}$$

D.2.4 Calculation of the dry to wet correction factor k_w

D.2.4.1 Stoichiometric combustion

The dry to wet correction factor $k_{w,r}$ is used for converting dry measured concentrations to the wet reference condition. $k_{w,r}$ is further the quotient between dry and wet exhaust volume flow:

$$k_{w,r} = \frac{c_{gasw}}{c_{gasd}} = \frac{q_{v_{ed}}}{q_{v_{ew}}} = 1 - \frac{q_{v_{H20}}}{q_{v_{ew}}} \tag{D.25}$$

The index "gas" indicates the individual gaseous component (e.g. CO). q_{vH20} here has to be interpreted as the water content of the exhaust, which condenses in the cooling bath of the gas analysis system and which is thus removed from the exhaust before measurement. q_{vH20} is calculated by adding the water from the intake air to the water formed by combustion and subtracting the rest water, which is still present after the cooling bath.

$$q_{v_{H20,intake\,air}} = \frac{q_{mad} \times H_a \times V_{m_{H20}}}{1\,000 \times M_{r_{H20}}} [m^3/h] \tag{D.26}$$

$$q_{v_{H20,formed\,by\,combustion}} = \frac{w_H \times q_{mf} \times V_{m_{H20}}}{100 \times 2 \times A_{r_H}} \quad [m^3/h] \tag{D.27}$$

$$q_{v_{H20,rest\,after\,cooler}} = \frac{q_{mad}}{1{,}293} \times \frac{p_r}{p_b} \quad [m^3/h] \tag{D.28}$$

with p_r = water partial pressure after cooling bath

and p_r/p_b = mole fraction of water vapor = volume fraction of water vapor after the cooler

and Density of dry air = 1,293 kg/m^3

$$q_{v_{ew}} = q_{v_{aw}} + q_{mf} \times f_{fw} \tag{D.29}$$

$$k_{w,r} = 1 - \frac{\dfrac{q_{mad} \times H_a \times V_{mH20}}{1\,000 \times M_{rH20}} + \dfrac{w_H \times q_{mf} \times V_{mH20}}{100 \times 2 \times A_{r_H}} - \dfrac{q_{mad} \times p_r}{1{,}293 \times p_b}}{\dfrac{q_{mad} \times H_a \times V_{mH20}}{1\,000 \times M_{rH20}} + \dfrac{q_{mad}}{1{,}293} + q_{mf} \times f_{fw}} \tag{D.30}$$

Dividing the numerator and denominator by 1 000/q_{mad} and substituting for known values of molar volumes, molecular masses and atomic masses, the following formula can be derived.

$$k_{w,r} = 1 - \frac{1{,}2442 \times H_a + 111{,}187 \times w_H \times \dfrac{q_{mf}}{q_{mad}} - 773{,}4 \times \dfrac{p_r}{p_b}}{773{,}4 + 1{,}244\,2 \times H_a + \dfrac{q_{mf}}{q_{mad}} \times f_{fw} \times 1\,000} \tag{D.31}$$

NOTE In ISO 8178-1:1996 the dry wet factor $k_{w,r}$ was calculated by means of the intermediate fuel specific constant f_{fh} according to Formula (D.32).

$$f_{fh} = \frac{111{,}187 \times w_H}{773{,}4 + \frac{q_{mf}}{q_{mad}} \times f_{fw} \times 1\,000} \text{ and } k_{w,r} = \left(1 - f_{fh} \times \frac{q_{mf}}{q_{mad}}\right) - k_{w2} + \frac{p_r}{p_b} \quad \text{(D.32)}$$

The f_{fh} concept was abandoned, because f_{fh} is not only fuel specific but also Lambda dependant and because Formula (D.30) or (D.31) gives better precision.

D.2.4.2 Incomplete combustion

The water content of the exhaust and the dry/wet factor $k_{w,r}$ can be calculated from the exhaust composition in the following way:

The water concentrations (in % units) can be directly derived from the CO_2 and CO concentrations with taking into account the H/C ratio α (assuming β = 1) and the fact, that one molecule water is formed from 2 atoms hydrogen. Additionally 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. Further the water in the intake air and the water still present after the gas cooler have to be considered,

$$c_{H2O,combustion,d} = 0{,}5 \times \alpha \times \left(c_{CO2d} + \frac{c_{COd}}{10^4}\right) - c_{H2d} \quad \text{(D.33)}$$

$$k_{w,r} = \frac{q_{V_{ed}}}{q_{V_{ew}}} = \frac{q_{V_{ed}}}{q_{V_{ed}} + q_{V_{H2O,combustion,d}} + q_{V_{H2O,a}} - q_{V_{H2O,after\ cooler}}} \quad \text{(D.34)}$$

where the concentration of H_2O, H_2 and CO_2 are expressed as a % and the concentration of CO is expressed in µmol/mol.

$$k_{w,r} = \frac{1}{1 + \frac{q_{V_{H2O,combustion,d}}}{q_{V_{ed}}} + \frac{q_{V_{H2O,ad}}}{q_{V_{ed}}} - \frac{q_{V_{H2O,after\ cooler}}}{q_{V_{ed}}}} \quad \text{(D.35)}$$

$$k_{w,r} = \frac{1}{1 + \frac{c_{H2O,combustion,d}}{100} + \frac{c_{H2O,ad}}{100} - \frac{c_{H2O,after\ cooler}}{100}} \quad \text{(D.36)}$$

$$k_{w,r2} = \frac{1}{1 + \alpha \times 0{,}005 \times \left[c_{CO2d} + \frac{c_{CO2d}}{10\,000}\right] - 0{,}01 \times c_{H2d} + k_{w2} - \frac{p_r}{p_b}} \quad \text{(D.37)}$$

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

$$k_{w2} = \frac{1{,}608 \times H_a}{1\,000 + (1{,}608 \times H_a)} \quad \text{(D.38)}$$

and H_a is the humidity of the intake air in g water per kg of dry air.

The concentration of hydrogen is derived from the water gas equilibrium according to the following formula based on SAE J 1088:

$$c_{\mathrm{H2d}}=\frac{0{,}5\times\alpha\times\dfrac{c_{\mathrm{COd}}}{10^4}\times\left(\dfrac{c_{\mathrm{COd}}}{10^4}+c_{\mathrm{CO2d}}\right)}{\dfrac{c_{\mathrm{COd}}}{10^4}+3\times c_{\mathrm{CO2d}}} \quad \text{(D.39)}$$

or

$$c_{\mathrm{H2}}\,[\%\,\mathrm{Vol}]=\frac{0{,}5\times\alpha\times c_{\mathrm{CO}}\,[\%\,\mathrm{Vol}]\times\left(c_{\mathrm{CO}}\,[\%\,\mathrm{Vol}]+c_{\mathrm{CO2}}\,[\%\,\mathrm{Vol}]\right)}{c_{\mathrm{CO}}\,[\%\,\mathrm{Vol}]+3\times c_{\mathrm{CO2}}\,[\%\,\mathrm{Vol}]} \quad \text{(D.40)}$$

This method of $k_{\mathrm{w,r}}$ calculation is to be preferred for rich fuel air mixtures (high CO values) and also for emission measurements without direct air flow measurements, because the $k_{\mathrm{w,r}}$ calculation by Formula (D.31) assumes stoichiometric combustion and it needs the data for q_{mad}.

D.2.5 Calculation of the dry and wet exhaust densities using f_{fw} and f_{ed}

The exhaust density is calculated by dividing the exhaust mass flow by the exhaust volume flow:

$$\rho_{\mathrm{ew}}=\frac{q_{mew}}{q_{V_{\mathrm{ew}}}}=\frac{q_{maw}+q_{mf}}{q_{V_{\mathrm{aw}}}+f_{\mathrm{fw}}\times q_{mf}}\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right] \quad \text{(D.41)}$$

$$\rho_{\mathrm{ew}}=\frac{q_{mad}+\dfrac{H_{\mathrm{a}}\times q_{mad}}{1\,000}+q_{mf}}{\dfrac{q_{mad}}{1{,}293}+\dfrac{q_{mad}\times H_{\mathrm{a}}\times V_{\mathrm{mH20}}}{1\,000\times M_{\mathrm{rH20}}}+f_{\mathrm{fw}}\times q_{mf}} \quad \text{(D.42)}$$

$$\rho_{\mathrm{ew}}=\frac{1\,000+H_{\mathrm{a}}+1\,000\times\dfrac{q_{mf}}{q_{mad}}}{773{,}4+1{,}2434\times H_{\mathrm{a}}+1\,000\times f_{\mathrm{fw}}\times\dfrac{q_{mf}}{q_{mad}}} \quad \text{(D.43)}$$

Calculation of the density of the dry exhaust:

$$\rho_{\mathrm{ed}}=\frac{q_{med}}{q_{V_{\mathrm{ed}}}}=\frac{q_{mad}+q_{mf}\times\left(1-\dfrac{w_{\mathrm{H}}}{100}\times\dfrac{M_{\mathrm{rH20}}}{2\times A_{\mathrm{rH}}}\right)}{q_{V_{\mathrm{ad}}}+f_{\mathrm{fd}}\times q_{mf}}\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right] \quad \text{(D.44)}$$

$$\rho_{\mathrm{ed}}=\frac{q_{mad}+q_{mf}\times\left(1-\dfrac{w_{\mathrm{H}}}{100}\times\dfrac{M_{\mathrm{rH20}}}{2\times A_{\mathrm{rH}}}\right)}{\dfrac{q_{mad}}{1{,}293}+f_{\mathrm{fd}}\times q_{mf}}=\frac{q_{mad}+q_{mf}\times(1-w_{\mathrm{H}}\times0{,}089\,36)}{\dfrac{q_{mad}}{1{,}293}+f_{\mathrm{fd}}\times q_{mf}} \quad \text{(D.45)}$$

D.3 Calculation of the exhaust mass flow from the exhaust composition (carbon and oxygen balance, for fuels with C, H, S, N and O)

D.3.1 General

In this annex 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 calculation formulae in this annex are related to the concentrations in the dry exhaust, whereas in the last revision a relation to the wet exhaust was used. The conversion was made because with the dry method a better precision of the calculated exhaust mass flow was reached especially for highly incomplete combustion situations (small gasoline engines).

The calculation of the exhaust mass flow can also be used for comparison with measured mass flows, in order to provide check methods regarding the plausibility of test results.

Low deviations between measured and calculated air flow indicate correct CO_2 or O_2 values (no leak in sampling system) and correct air flow measurement (no leak in connection tubes between engine and air flow equipment) and correct fuel measurement.

Differences between measured and calculated air flows give hints for the following errors:

a) Measured air flow lower than by carbon balance method:

- leak in exhaust sampling system (highest probability); or
- leak in air measurement equipment (moderate probability); or
- too high fuel flow values (low probability, except for idle).

b) Measured air flow higher than by carbon balance method:

- calibration error of exhaust analyser; or
- calibration error of air measurement equipment; or
- too low fuel flow values.

NOTE All these cases of a) are less probable than the three cases of b).

When using the carbon or oxygen balance method for calculation of emissions a leak in the exhaust sampling system has no severe effect on the results, because the too low exhaust concentrations are compensated by correspondingly too high calculated exhaust mass flows, so these effects compensate each other.

For the derivations within D.3.2 and D.3.3 it is assumed that the fuel consumption, the fuel composition and the concentration of the exhaust components are known. It is applicable for fuels containing H, C, S, O and N in known proportions.

D.3.2 Calculation of the exhaust mass flow on the basis of the carbon balance

D.3.2.1 General

In this clause two forms of the carbon balance method are given, an iterative calculation (multi-step) procedure and a one-step calculation procedure. The one-step procedure was added within the revision of this document, because it is easier to use than the multi-step procedure.

D.3.2.2 Carbon balance, iterative calculation procedure

The calculation of q_{med}, as described in the following clause, 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 (or multi-step) calculation procedure has to be applied in the following way. With preliminary values of

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 would not be necessary.

D.3.2.2.1 Formulae for the calculation of the exhaust mass flow

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

$$q_{med} = \frac{q_{mf} \times w_C \times \rho_{ed} \times 10^4}{A_{rC} \times \left(\left(\frac{(c_{CO2d} - c_{CO2,a}) \times 10^4}{V_{mCO2}} + \frac{c_{COd}}{V_{mCO}} \right) \times \frac{1}{1 - \frac{p_r}{p_b}} + \left(\frac{c_{HCw}}{V_{mHC}} + \frac{c_{Cw}}{A_{rC}} \right) \times \frac{1}{k_{wr}} \right)} \quad \text{(D.46)}$$

$$q_{mad} = q_{med} - q_{mf} \times \left(1 - \frac{w_H}{100} \times \frac{M_{rH2O}}{2 \times A_{rH}} \right) \quad \text{(D.47)}$$

$$= q_{med} - q_{mf} \times (1 - w_H \times 0{,}089\,36)$$

$$q_{mew} = q_{mad} \times \left(1 + \frac{H_a}{1\,000} \right) + q_{mf} \quad \text{(D.48)}$$

Inserting concrete numbers into Formula (D.46) results in the following formulae for incomplete combustion

$$q_{med} = \frac{q_{mf} \times w_C \times \rho_{ed} \times 832{,}57}{\left(\left((c_{CO2} - c_{CO2a}) \times 446{,}1 + \frac{c_{COd}}{22{,}414} \right) \times \frac{1}{1 - \frac{p_r}{p_b}} + \left(\frac{c_{HCw}}{22{,}414} + \frac{c_{Cw}}{12{,}011} \right) \times \frac{1}{k_{wr}} \right)} \quad \text{(D.49)}$$

and for complete combustion

$$q_{med} = q_{mf} \times \frac{\rho_{ed} \times 1{,}866\,3}{(c_{CO2d} - c_{CO2,a})} \quad \text{(D.50)}$$

Combining Formulae (D.49), (D.47) and (D.48) in one formula and using some simplifications (neglecting unburned soot and assuming a fixed cooler temperature of 4 °C, i.e. $1/(1 - p_r/p_b) = 1{,}008$) the following easier to use formula for the wet exhaust mass flow results:

$$q_{mew} = q_{mf} \times \left(\left(\left(\frac{w_C \times \rho_{ed}}{(c_{CO2d} - c_{CO2,a}) \times 0{,}540 + \frac{c_{COd} + \frac{c_{HC_w}}{k_{wr}}}{10\,000} \times 0{,}540} + w_H \times 0{,}089\,36 - 1 \right) \times \left(1 + \frac{H_a}{1\,000} \right) \right) + 1 \right) \quad \text{(D.51)}$$

For combustion of typical diesel fuel with w_C = 86,2 % mass and ρ_{ed} = 1,329 (excess air factor of 2) the following further simplified formula can be given:

$$q_{mew} = q_{mf} \times \left(\left(\left(\frac{1}{\left(c_{\mathrm{CO2d}} - c_{\mathrm{cCO2,a}}\right) \times 0{,}004\,71 + \dfrac{c_{\mathrm{COd}} + \dfrac{c_{\mathrm{HCw}}}{k_{\mathrm{wr}}}}{10\,000} \times 0{,}004\,71} + w_{\mathrm{H}} \times 0{,}089\,36 - 1 \right) \times \left(1 + \frac{H_{\mathrm{a}}}{1\,000}\right) \right) + 1 \right) \tag{D.52}$$

D.3.2.2.2 Derivation of formulae

The carbon input [g/h] into the engine from the fuel is:

$$q_{mf} \times w_{\mathrm{C}} \times 10 \tag{D.53}$$

The carbon input [g/h] into the engine from the intake air is $q_{m\mathrm{CO2,a}}$. See Formula (D.56).

The carbon output from the engine in g/h is:

$$q_{m\mathrm{CO2}} \times \frac{A_{\mathrm{rC}}}{M_{\mathrm{rCO2}}} + q_{m\mathrm{CO}} \times \frac{A_{\mathrm{rC}}}{M_{\mathrm{rCO}}} + q_{m\mathrm{HC}} \times \frac{A_{\mathrm{rC}}}{M_{\mathrm{rHC}}} + q_{m\mathrm{C}} \tag{D.54}$$

With the following formulae the individual gas components are calculated in g/h.

$$q_{m\mathrm{CO2}} = \frac{M_{\mathrm{rCO2}} \times 10}{V_{\mathrm{mCO2}} \times \rho_{\mathrm{ed}}} \times \frac{c_{\mathrm{CO2d}}}{1 - \dfrac{p_{\mathrm{r}}}{p_{\mathrm{b}}}} \times q_{med} \tag{D.55}$$

In Formula (D.55) the CO_2 mass emission is calculated from the volume portion by multiplication with the quotient of the gas densities (CO_2/dry exhaust). The CO_2 gas density is given as molecular weight per molecular volume. These principal formulae are used in comparable way for the other components:

$$q_{m\mathrm{CO2,a}} = \frac{M_{\mathrm{rCO2}} \times 10}{V_{\mathrm{mCO2}} \times \rho_{\mathrm{ed}}} \times \frac{c_{\mathrm{CO2,a}}}{1 - \dfrac{p_{\mathrm{r}}}{p_{\mathrm{b}}}} \times q_{med} \tag{D.56}$$

$$q_{m\mathrm{CO}} = \frac{M_{\mathrm{rCO}}}{V_{\mathrm{mCO}} \times \rho_{\mathrm{ed}} \times 1\,000} \times \frac{c_{\mathrm{COd}}}{1 - \dfrac{p_{\mathrm{r}}}{p_{\mathrm{b}}}} \times q_{med} \tag{D.57}$$

$$q_{m\mathrm{HC}} = \frac{M_{\mathrm{rHC}}}{V_{\mathrm{mHC}} \times \rho_{\mathrm{ed}} \times 1\,000} \times \frac{c_{\mathrm{HCw}}}{k_{\mathrm{wr}}} \times q_{med} \tag{D.58}$$

$$q_{mC}=\frac{1}{\rho_{ed}\times 1\,000}\times\frac{c_{Cw}}{k_{wr}}\times q_{med} \qquad \text{(D.59)}$$

The balance condition (carbon input = carbon output) results in

$$q_{mf}\times w_{C}\times 10=\frac{q_{med}\times A_{rC}}{\rho_{ed}\times 1\,000}\times\left(\frac{\left(c_{CO2d}-c_{CO2,a}\right)\times 10^{4}}{V_{mCO2}\times 1-\frac{p_{r}}{p_{b}}}+\frac{c_{COd}}{V_{mCO}\times\left(1-\frac{p_{r}}{p_{b}}\right)}+\frac{c_{HCw}}{V_{mHC}\times k_{wr}}+\frac{c_{Cw}}{A_{rC}\times k_{wr}}\right) \qquad \text{(D.60)}$$

Formula (D.60) can be converted to Formula (D.61), allowing the calculation of q_{med} on the basis of the carbon balance:

$$q_{med}=\frac{q_{mf}\times w_{C}\times\rho_{ed}\times 10^{4}}{A_{rC}\times\left[\frac{\frac{\left(c_{CO2d}-c_{CO2,a}\right)\times 10^{4}}{V_{mCO2}}+\frac{c_{COd}}{V_{mCO}}}{1-\frac{p_{r}}{p_{b}}}+\frac{c_{HCw}}{k_{wr}\times V_{mHC}}+\frac{c_{Cw}}{k_{wr}\times A_{rC}}\right]} \qquad \text{(D.61)}$$

D.3.2.3 Carbon balance, 1-step calculation procedure

Because of the not so easy to use multi-step calculation procedure, in this clause two iteration steps are combined in one final formula for the exhaust mass flow, thus enabling a 1-step calculation procedure. The results of the 1-step procedure are within ±0,2 % of the multi-step procedure for all fuel compositions tested.

D.3.2.3.1 Carbon balance, 1-step calculation procedure, application of formulae

The following 1-step formula can be used for the calculation of the wet exhaust mass flow:

$$q_{mew}=q_{mf}\times\left(\left(\frac{\frac{w_{C}\times w_{C}\times 1{,}4}{\left(\frac{1{,}4\times w_{C}}{f_{c}}+w_{H}\times 0{,}089\,36-1\right)\times\frac{1}{1{,}293}+f_{fd}}}{f_{c}\times f_{c}}+w_{H}\times 0{,}089\,36-1\right)\times\left(1+\frac{H_{a}}{1\,000}\right)+1\right) \qquad \text{(D.62)}$$

with the carbon factor f_c [–] given by:

$$f_{c}=\left(c_{CO2d}-c_{CO2,a}\right)\times 0{,}544\,1+\frac{c_{COd}}{18\,522}+\frac{c_{HCw}}{17\,355} \qquad \text{(D.63)}$$

or

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

$$q_{m_{ew}}=q_{m_{f}}\times\left(\frac{w_{C}\times w_{C}\times 1{,}4}{\left(1{,}082\,8\times w_{C}+f_{fd}\times f_{c}\right)\times f_{c}}\times\left(1+\frac{H_{a}}{1\,000}\right)+1\right) \qquad \text{(D.64)}$$

NOTE 1 Formula (D.65) is given as a simpler version of Formula (D.63) without significant loss of precision.

NOTE 2 See Annex E for an example for the calculation of exhaust mass flows.

D.3.2.3.2 Carbon balance, 1-step procedure, derivation of formulae

In the paragraph the quotient q_{mad}/q_{mf} is calculated, using Formula (D.50), repeated here as Formula (D.66):

$$q_{med} = \frac{q_{mf} \times w_{\mathrm{C}} \times \rho_{\mathrm{ed}} \times 832{,}57}{\left(\left(\left(c_{\mathrm{CO2}} - c_{\mathrm{CO2,a}} \right) \times 446{,}1 + \frac{c_{\mathrm{COd}}}{22{,}414} \right) \times \frac{p_{\mathrm{b}}}{p_{\mathrm{b}} - p_{\mathrm{r}}} + \left(\frac{c_{\mathrm{HCw}}}{22{,}414} + \frac{c_{\mathrm{Cw}}}{12{,}011} \right) \times \frac{1}{k_{\mathrm{wr}}} \right)} \tag{D.65}$$

with

p_{b} = 1 013 mbar and p_{r} = 7,5 mbar (4 °C cooler temperature), or $p_{\mathrm{b}}/(p_{\mathrm{b}} - p_{\mathrm{r}})$ = 1,008, with $k_{\mathrm{w,r}}$ = 0,93 and c_{Cw} = 0 this formula is simplified to:

$$q_{med} = \frac{q_{mf} \times w_{\mathrm{C}} \times \rho_{\mathrm{ed}}}{\left(c_{\mathrm{CO2d}} - c_{\mathrm{CO2a}} \right) \times 0{,}544\,1 + \frac{c_{\mathrm{COd}}}{18\,522} + \frac{c_{\mathrm{HCW}}}{17\,355}} = \frac{q_{mf} \times w_{\mathrm{C}} \times \rho_{\mathrm{ed}}}{f_{\mathrm{c}}} \tag{D.66}$$

with

$$f_{\mathrm{c}} = \left(c_{\mathrm{CO2}d} - c_{\mathrm{CO2,a}} \right) \times 0{,}544\,1 + \frac{c_{\mathrm{COd}}}{18\,522} + \frac{c_{\mathrm{HCw}}}{17\,355} \tag{D.67}$$

$$\begin{aligned} q_{mad} &= q_{med} - q_{mf} \times \left(1 - \frac{w_{\mathrm{H}}}{100} \times \frac{M_{\mathrm{rH2O}}}{2 \times A_{\mathrm{rH}}} \right) \\ &= q_{med} - q_{mf} \times (1 - w_{\mathrm{H}} \times 0{,}089\,36) \end{aligned} \tag{D.68}$$

$$\frac{q_{mad}}{q_{mf}} = \frac{w_{\mathrm{C}} \times \rho_{\mathrm{ed}}}{f_{\mathrm{c}}} + 0{,}089\,36 \times w_{\mathrm{H}} - 1 \tag{D.69}$$

Calculation of dry exhaust density ρ_{ed} using the ratio q_{mad}/q_{mf} from Formula (D.69):

slight conversion of Formula (D.45):

$$\rho_{\mathrm{ed}} = \frac{q_{mad} + q_{mf} \times \left(1 - \frac{w_{\mathrm{H}}}{100} \times \frac{M_{\mathrm{rH2O}}}{2 \times A_{\mathrm{rH}}} \right)}{\frac{q_{mad}}{1{,}293} + f_{\mathrm{fd}} \times q_{mf}} = \frac{\frac{q_{mad}}{q_{mf}} + 1 - 0{,}089\,36 \times w_{\mathrm{H}}}{\frac{q_{mad}}{1{,}293 \times q_{mf}} + f_{\mathrm{fd}}} \tag{D.70}$$

and insertion of Formula (D.69) leads to:

$$\rho_{\mathrm{ed}} = \frac{\frac{w_{\mathrm{C}} \times \rho_{\mathrm{ed,p}}}{f_{\mathrm{c}}} + 0{,}089\,36 \times w_{\mathrm{H}} - 1 + 1 - 0{,}089\,36 \times w_{\mathrm{H}}}{\left(\frac{w_{\mathrm{C}} \times \rho_{\mathrm{ed,p}}}{f_{\mathrm{c}}} + 0{,}089\,36 \times w_{\mathrm{H}} - 1 \right) \times \frac{1}{1{,}293} + f_{\mathrm{fd}}} \tag{D.71}$$

and finally to:

$$\rho_{\mathrm{ed}} = \frac{\frac{w_{\mathrm{C}} \times \rho_{\mathrm{ed,p}}}{f_{\mathrm{c}}}}{\left(\frac{w_{\mathrm{C}} \times \rho_{\mathrm{ed,p}}}{f_{\mathrm{c}}} + 0{,}089\,36 \times w_{\mathrm{H}} - 1 \right) \times \frac{1}{1{,}293} + f_{\mathrm{fd}}} \tag{D.72}$$

In this formula $\rho_{\mathrm{ed,p}}$ is a preliminary value of the dry exhaust density (target value: $\rho_{\mathrm{ed,p}}$ = 1,34), which is here calculated more exactly to the final value ρ_{ed} for further use in the next step.

Use of ρ_{ed} in the calculation of the exhaust mass flow:

Combining Formulae (D.47) and (D.48) leads to:

$$q_{mew} = q_{mad} \times \left(1 + \frac{H_a}{1\,000}\right) + q_{mf}$$
$$= (q_{med} - q_{mf} \times (1 - w_H \times 0{,}089\,36)) \times \left(1 + \frac{H_a}{1\,000}\right) + q_{mf} \quad \text{(D.73)}$$

which is with the use of

$$q_{med} = \frac{q_{mf} \times w_C \times \rho_{ed}}{f_c} \quad \text{(D.74)}$$

further transformed to

$$q_{mew} = q_{mf} \times \left(\left(\frac{w_C \times \rho_{ed}}{f_c} - (1 - w_H \times 0{,}089\,36 \right) \times \left(1 + \frac{H_a}{1\,000}\right) + 1 \right) \quad \text{(D.75)}$$

Inserting ρ_{ed} from Formula (D.72) into this formula leads to the final formulae given in D.3.2.3.1.

D.3.3 Oxygen balance, iterative calculation procedure

D.3.3.1 General

The oxygen balance method gives slightly higher deviations compared to theoretical exhaust mass flows (up to 1 % compared to the carbon balance method with below 0,2 %). Therefore the carbon balance method should be the preferred method. But the oxygen balance method can be used as an independent check of the other methods.

D.3.3.2 Application of formulae

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

$$q_{med} = q_{mf} \times \left\{ \frac{\left(1 - \frac{w_H}{100} \times \frac{M_{rH20}}{2 \times A_{rH}}\right) \times w_{ox} \times 10 + 10 \times f_2 - 10 \times w_O}{w_{ox} \times 10 - \frac{f_1}{1\,000 \times \rho_{ed}}} \right\} \quad \text{(D.76)}$$

which transforms to the following formula upon substitution:

$$q_{med} = q_{mf} \times \frac{(1 - 0{,}089\,36 \times w_H) \times w_{ox} + f_2 - w_O}{w_{ox} - \frac{f_1}{10\,000 \times \rho_{ed}}} \quad \text{(D.77)}$$

$$q_{mew} = q_{mad} \times \left(1 + \frac{H_a}{1\,000}\right) + q_{mf} \tag{D.78}$$

$f1$ and $f2$ used in Formula (D.76) and (D.77) are defined as:

$$f_1 = \left(10\,000 \times \frac{M_{rO2} \times c_{CO2d}}{V_{mO2}} - \frac{A_{rO}}{V_{mCO}} \times c_{COd}\right) \times \frac{1}{1 - \frac{p_r}{p_b}} + \frac{\left(\frac{A_{rO}}{V_{mNO}} \times c_{NOw} + \frac{2 \times A_{rO}}{V_{mNO2}} \times c_{NO2w} - \frac{3 \times A_{rO}}{V_{mHC}} \times c_{HCw} - \frac{2 \times A_{rO}}{A_{rC}} \times c_{Cw}\right)}{k_{wr}} \tag{D.79}$$

and

$$f_2 = w_H \times \frac{A_{rO}}{2 \times A_{rH}} + w_C \times \frac{2 \times A_{rO}}{A_{rC}} + w_S \times \frac{2 \times A_{rO}}{A_{rS}} \tag{D.80}$$

Simplification with complete combustion:

$$f_{1complete} = \left(10\,000 \times \frac{M_{rO2}}{V_{mO2}} \times c_{O2d}\right) \Big/ \left(1 - \frac{p_r}{p_b}\right) \tag{D.81}$$

Insertion of concrete numbers:

$$f_1 = \frac{14\,276 \times c_{O2d} - 0{,}713\,8 \times c_{COd}}{1 - \frac{p_r}{p_b}} + \frac{0{,}713\,8 \times c_{NOw} + 1{,}427\,6 \times c_{NO2w} - 2{,}141\,4 \times c_{HCw} - 2{,}664\,1 \times c_{Cw}}{k_{wr}} \tag{D.82}$$

Simplification with complete combustion

$$f_1 = \frac{14\,276 \times c_{O2d}}{1 - \frac{p_r}{p_h}} \tag{D.83}$$

$$f_2 = w_H \times 7{,}936\,7 + w_C \times 2{,}664\,1 + w_S \times 0{,}997\,9 \tag{D.84}$$

D.3.3.3 Derivation of formulae

The oxygen input [g/h] into the engine from the air and from the fuel is:

$$q_{mad} \times w_{ox} \times 10 + q_{mf} \times w_{O} \times 10 \quad (D.85)$$

By calculation of the oxygen content of each oxygen containing exhaust constituent the total oxygen (free and chemically bound) the oxygen output from the engine in g/h can be given as:

$$q_{mO2} + q_{mCO2} \times \frac{2 \times A_{rO}}{M_{rCO2}} + q_{mCO} \times \frac{A_{rO}}{M_{rCO}} + q_{mNO} \times \frac{A_{rO}}{M_{rNO}} + q_{mNO2} \times \frac{2 \times A_{rO}}{M_{rNO2}} + q_{mSO2} \times \frac{2 \times A_{rO}}{M_{rSO2}} + q_{mHO2} \times \frac{A_{rO}}{M_{rH2O}} \quad (D.86)$$

With the following formulae the individual gas components are calculated in g/h.

$$q_{mO2} = \frac{M_{rO2} \times 10}{V_{mO2} \times \rho_{ed}} \times \frac{c_{O2d}}{1 - \frac{p_r}{p_b}} \times q_{med} \quad (D.87)$$

$$q_{mCO} = \frac{M_{rCO}}{V_{mCO} \times \rho_{ed} \times 1\,000} \times \frac{c_{COd}}{1 - \frac{p_r}{p_b}} \times q_{med} \quad (D.88)$$

$$q_{m_{NO}} = \frac{M_{rNO}}{V_{mNO} \times \rho_{ed} \times 1\,000} \times \frac{c_{NOw}}{k_{wr}} \times q_{med} \quad (D.89)$$

$$q_{m_{NO2}} = \frac{M_{rNO2}}{V_{mNO2} \times \rho_{ed} \times 1\,000} \times \frac{c_{NO2w}}{k_{wr}} \times q_{med} \quad (D.90)$$

$$q_{mCO} = \frac{M_{rCO2}}{A_{rC}} \times q_{mf} \times w_{C} \times 10 - q_{mCO} \times \frac{M_{rCO2}}{M_{rCO}} - q_{mHC} \times \frac{M_{rCO2}}{M_{rHC}} - q_{mC} \times \frac{M_{rCO2}}{A_{rC}} \quad (D.91)$$

$$q_{mH2O} = \frac{M_{rH2O}}{2 \times A_{rH}} \times q_{mf} \times w_{H} \times 10 - q_{mHC} \times \frac{M_{rH2O}}{M_{rHC}} \quad (D.92)$$

$$q_{mSO2} = \frac{M_{rSO2}}{A_{rS}} \times q_{mf} \times w_{S} \times 10 \quad (D.93)$$

$$q_{mHC} = \frac{M_{rHC}}{V_{mHC} \times \rho_{ed} \times 1\,000} \times \frac{c_{HCw}}{k_{wr}} \times q_{med} \quad (D.94)$$

$$q_{mC} = \frac{1}{\rho_{ed} \times 1\,000} \times \frac{c_{Cw}}{k_{wr}} \times q_{med} \tag{D.95}$$

The balance condition (oxygen input = oxygen output) results in

$$\begin{aligned} & q_{mad} \times w_{ox} \times 10 + q_{mf} \times w_O \times 10 \\ & = \frac{q_{med}}{1\,000 \times \rho_{ed}} \\ & \times \left\{ \frac{\frac{M_{rO2} \times c_{O2d} \times 10\,000}{V_{mO2}} - \frac{A_{rO} \times c_{COd}}{V_{mCO}}}{1 - \frac{p_r}{p_b}} \right. \\ & \left. + \frac{\frac{A_{rO} \times c_{NOw}}{V_{mNO}} + \frac{2 \times A_{rO} \times c_{NO2w}}{V_{mNO2}} - \frac{3 \times A_{rO} \times c_{HCw}}{V_{mHC}} - \frac{2 \times A_{rO} \times c_{Cw}}{A_{rC}}}{k_{wr}} \right\} \\ & + 10 \times q_{m_f} \times \left(w_H \times \frac{A_{rO}}{2 \times A_{rH}} + w_C \times \frac{2 \times A_{rO}}{A_{rC}} + w_S \times \frac{2 \times A_{rO}}{A_{rS}} \right) \end{aligned} \tag{D.96}$$

By defining the following factors

$$f_1 = \frac{\frac{M_{rO2} \times c_{O2d} \times 10\,000}{V_{mO2}} - \frac{A_{rO} \times c_{COd}}{V_{mCO}}}{1 - \frac{p_r}{p_b}} + \frac{\frac{A_{rO} \times c_{NOw}}{V_{mNO}} + \frac{2 \times A_{rO} \times c_{NO2w}}{V_{mNO2}} - \frac{3 \times A_{rO} \times c_{HCw}}{A_{mHC}} - \frac{2 \times A_{rO} \times c_{Cw}}{A_{rC}}}{k_{wr}} \tag{D.97}$$

$$f_2 = \left(w_H \times \frac{A_{rO}}{2 \times A_{rH}} + w_C \times \frac{2 \times A_{rO}}{A_{rC}} + w_S \times \frac{2 \times A_{rO}}{A_{rS}} \right) \tag{D.98}$$

and by using Formula (D.47), Formula (D.96) can be converted to the following formula:

$$q_{med} = q_{mf} \times \left\{ \frac{\left(1 - \frac{w_H}{100} \times \frac{M_{rH2O}}{2 \times A_{rH}} \right) \times w_{ox} \times 10 + 10 \times f_2 - 10 \times w_O}{w_{ox} \times 10 - \frac{f_1}{1\,000 \times \rho_{ed}}} \right\} \tag{D.99}$$

which is equivalent to Formula (D.76) given in the beginning.

D.4 Derivation of the fuel specific factor k_f

The following formulae are essential for the carbon balance method for partial flow particulates measurement system.

$$q = \frac{k_f \times q_{mf}}{q_{mew} \times (c_{CO2d} - c_{CO2,a})} \tag{D.100}$$

and

$$q_{medf} = \frac{k_f \times q_{mf}}{c_{CO2d} - c_{CO2,a}} \tag{D.101}$$

q_{medf} is defined as the mass flow of diluted exhaust in an equivalent full flow dilution tunnel (same dilution ratio).

This carbon balance method supposes that the carbon input from the fuel into the engine

$$q_{mf} \times w_C \times 10 [g/h] \tag{D.102}$$

is equal to the carbon output in the diluted exhaust, the latter being calculated from the CO_2-concentration in the diluted exhaust (minus the CO_2-concentration of the dilution air) in the following way:

$$\frac{q_{medf}}{\rho_{ew,d}} \times (c_{CO2d} - c_{CO2,a}) \times \frac{A_{rC} \times 10}{V_{mCO2}} \tag{D.103}$$

The balance condition (input = output) together with Formula (D.101) can be converted to the following formula for k_f:

$$k_f = \frac{w_C \times V_{mCO2} \times \rho_{ew,d}}{A_{rC}} \tag{D.104}$$

The density of the diluted exhaust $\rho_{ew,d}$ can be calculated from the density of the dry dilution air (1,293 kg/m^3), from the water content of the dilution air

$$\rho_{ew,d} = 1{,}293 \times k_{we} + \frac{M_{rH2O}}{V_{mH2O}} \times (1 - k_{we}) \tag{D.105}$$

with the factor k_{we} from 9.1.5.2.

With dry dilution air and with high dilution ratios ($\rho_{ew,d}$ = 1,293 kg/m^3) and with V_{mCO2} = 22,414 and A_{rC} = 12,011 the following simpler formula results:

$$k_f = w_C \times 2{,}412\,9 \tag{D.106}$$

Figure D.1 gives some guidance to the application of formulae for the different possibilities to calculate the exhaust emissions:

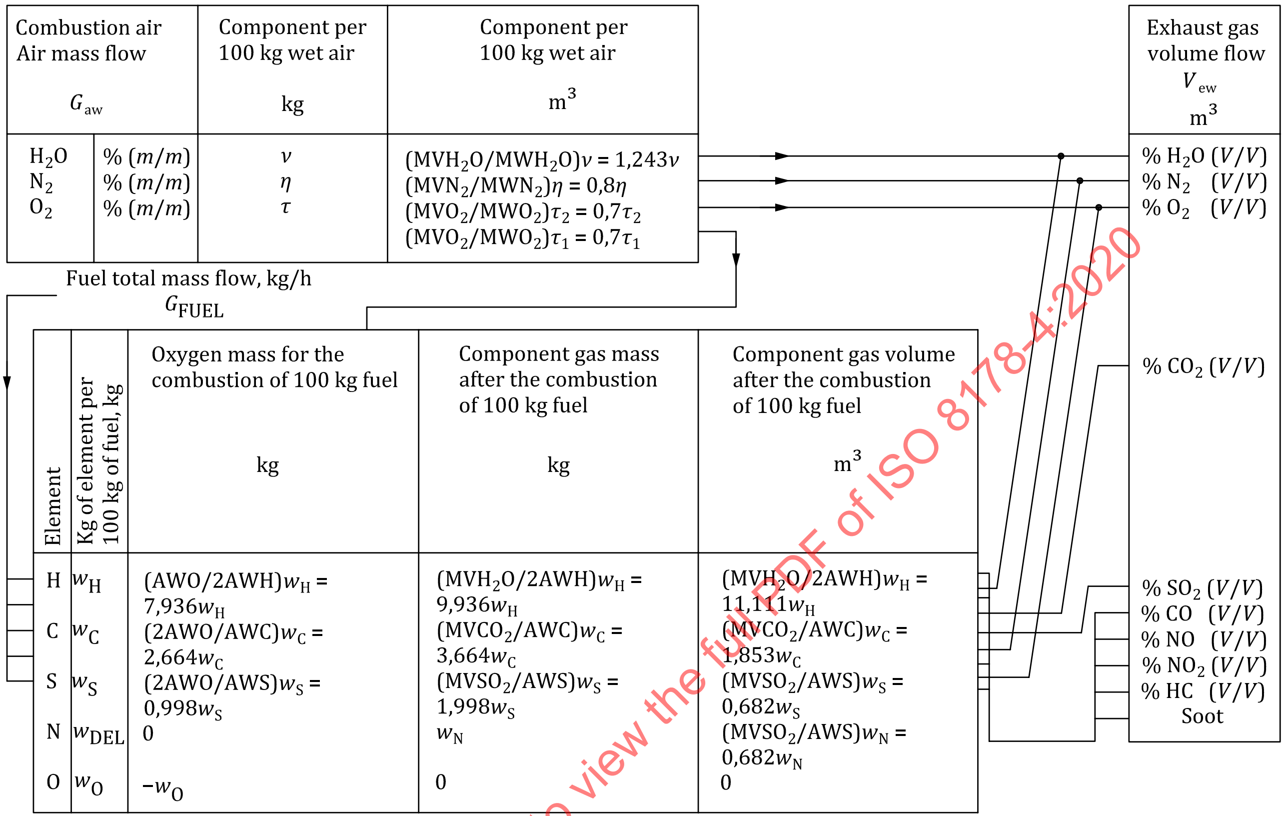


Figure D.1 — Air-fuel-exhaust gas

Annex E
(informative)

Example programme for calculation of exhaust mass flows

An example for calculation of the exhaust mass flows by exhaust and fuel composition according to Annex D is given in Table E.1 and Figure E.1.

Table E.1 — Example for calculation of exhaust mass flows

Basic data	Relative atomic mass/Molar mass	Molar volume
	g/mol	l/mol(0 C, 1 013 mbar)
H	1,007 94	
C	12,011 00	
S	32,060 00	
N	14,006 70	
O	15,999 40	
Ar	39,900 00	
H_2O	18,015 34	22,401 0
CO_2	44,010 00	22,262 0
O_2	31,998 80	22,392 0
NO_2	46,008 00	21,809 0
inert gases	28,145 40	22,390 1