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Reciprocating internal combustion engines — Exhaust emission measurement —

Part 9:
Test cycles and test procedures for measurement of exhaust gas smoke emissions from compression ignition engines using an opacimeter

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

Partie 9: Cycles et procédures d'essai pour le mesurage au banc d'essai des émissions de fumées de gaz d'échappement des moteurs alternatifs à combustion interne à allumage par compression fonctionnant en régime transitoire

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ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Fax: +41 22 749 09 47
Email: copyright@iso.org
Website: www.iso.org

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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).

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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.

This document was prepared by Technical Committee ISO/TC 70, *Internal combustion engines*, Subcommittee SC 8, *Exhaust gas emission measurement*.

This third edition cancels and replaces ISO 8178-9:2012 and ISO 8178-10:2002, which have been technically revised.

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

— ISO 8178-10:2002 has been incorporated in this document;

— terms and definitions have been harmonized within the ISO 8178 series and differences to other ISO standards have been described where applicable;

— redundant specifications of testing equipment, calibration and verification requirements have been deleted or replaced by references to other parts of the ISO 8178 series;

— ambient density smoke correction has been deleted;

— order of annexes has been changed;

— Annex A has been added - Overview particulate and soot measurement methods;

— Annex H has been added - Test at steady speeds over full-load curve;

— Annex I has been added - Reporting smoke tests results.

A list of all 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

On a global scale, there are currently many smoke measurement procedures in various forms. Some of these smoke measurement procedures are designed for test bed testing and intended to be used for certification or type-approval purposes. Others are designed for field-testing and can be used in inspection and maintenance programs. Different smoke measurement methods exist to meet the needs of various regulatory agencies and industries.

The two smoke measurement methods typically used are (1) the FSN method, measuring light absorption based on the change in optical reflectance of visible light from a blackening filter paper relative to the clean filter (filter-type smoke meters) and (2) the exhaust gas opacity method, measuring transmittance based on light extinction caused by absorption and scattering of light (opacimeter-type smoke meters).

Figure A.1 in Annex A shows an overview of the measurement methods specified by an ISO standard including FSN and opacity respectively.

ISO 8178-4 specifies a number of different test cycles to be used to characterize and control gaseous and particulate emissions from nonroad engines using a variety of steady-state and transient operating conditions. The test cycles in ISO 8178-4 were developed in recognition of the differing operating characteristics of various categories of nonroad machines. Likewise, different smoke test cycles can be appropriate for different categories of nonroad engines and machines.

Reciprocating internal combustion engines — Exhaust emission measurement —

Part 9: Test cycles and test procedures for measurement of exhaust gas smoke emissions from compression ignition engines using an opacimeter

1 Scope

This document specifies the measurement procedures and test cycles for the evaluation of smoke emissions from compression ignition engines using an opacimeter. The tests are carried out under steady-state and transient operation using tests cycles which are representative of a given application.

The smoke testing is conducted using opacimeter-type smoke meters which operate on the light extinction principle. The purpose of this document is to define the smoke test cycles and the methods used to measure the opacity and for the determination of the light absorption coefficient. It allows the use of either full-flow or partial-flow opacimeters and corrects for differences in rise time between the two types of opacimeters. Specifications of the apparatus for the measurement of opacity can be found in ISO 11614. The test procedures and measurement techniques described in this document are applicable to reciprocating internal combustion (RIC) engines in general. Annex D, Annex E, Annex F and Annex G each contains a test cycle that is relevant only for those specific applications listed in the first subclause of that annex. Where possible, the smoke test cycle described in the annex utilizes the engine and machine categories developed in ISO 8178-4.

For certain categories of non-road engines "at site" rather than "test bed" smoke test procedures can prove to be necessary. For engines used in machinery covered by additional requirements (e.g. occupational health and safety regulations), 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:—[1)], *Reciprocating internal combustion engines — Exhaust emission measurement — Part 1: Test-bed measurement systems of gaseous and particulate emissions*

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

ISO 8178-4:—[2)], *Reciprocating internal combustion engines — Exhaust emission measurement — Part 4: Steady-state and transient test cycles for different engine applications*

ISO 8178-7, *Reciprocating internal combustion engines — Exhaust emission measurement — Part 7: Engine family determination*

1) Under preparation.

2) Under preparation.

ISO 8178-8, *Reciprocating internal combustion engines — Exhaust emission measurement — Part 8: Engine group determination*

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

ISO 11614:1999, *Reciprocating internal combustion compression-ignition engines — Apparatus for measurement of the opacity and for determination of the light absorption coefficient of exhaust gas*

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
exhaust gas smoke
visible suspension of solid and/or liquid particles in gases resulting from combustion or pyrolysis

Note 1 to entry: The exhaust gas smoke may be black smoke, blue smoke, brown smoke or white smoke depending on the components present in the exhaust gas after the combustion or pyrolysis process. Black smoke (also referred to as “soot”) is mainly due to the presence of carbon particles. Blue smoke is usually due to droplets resulting from the incomplete combustion of fuel or lubricating oil. Brown smoke is due to the presence of NO_2 in the exhaust gas. White smoke is usually due to condensed water and/or liquid fuel.

3.2
transmittance
τ
fraction of light transmitted from a source through a smoke-obscured path which reaches the observer or the instrument receiver

Note 1 to entry: Transmittance is expressed as a percentage.

3.3
opacity
N
fraction of light transmitted from a source through a smoke-obscured path which is prevented from reaching the observer or the instrument receiver

Note 1 to entry: Opacity is expressed as a percentage.

Note 2 to entry: $N = 100 - \tau$.

3.4
effective optical path length
L_A
length of the smoke-obscured optical path between the *opacimeter* (3.8) light source and the receiver

Note 1 to entry: Effective optical path length is expressed in meters and corrected, as necessary, for non-uniformity due to density gradients and fringe effect.

3.5
standard effective optical path length
L_{AS}
measurement used to ensure meaningful comparisons of quoted *opacity* (3.3) values

Note 1 to entry: L_{AS} values are defined in 9.1.4.

3.6
light absorption coefficient
k
fundamental property quantifying the ability of a smoke plume or smoke-containing gas sample to obscure light

Note 1 to entry: Light absorption coefficient is expressed in reciprocal meters (m^{-1}).

3.7
Beer-Lambert law
mathematical equation describing the physical relationships between the *light absorption coefficient (k)* (3.6), *transmittance (τ)* (3.2) and *effective optical path length (LA)* (3.4)

Note 1 to entry: Because the light absorption coefficient (k) cannot be measured directly, the Beer-Lambert law is used to calculate k, when *opacity (N)* (3.3) or transmittance (τ) and effective optical path length (L_A) are known.

$$k = \frac{-1}{L_A} \times \ln\left(\frac{\tau}{100}\right) \tag{1}$$

$$k = \frac{-1}{L_A} \times \ln\left(1 - \frac{N}{100}\right) \tag{2}$$

3.8
opacimeter
instrument used for continuous measurement of *opacity* (3.3) and *light absorption coefficient* (3.6) of the exhaust gas

3.9
full-flow opacimeter
instrument which measures all flow of exhaust gas passing through the smoke measuring chamber

3.10
full-flow end-of-line opacimeter
instrument which measures the *opacity* (3.3) of the full exhaust plume as it exits at tailpipe

3.11
full-flow in-line opacimeter
instrument which measures the *opacity* (3.3) of the full exhaust plume within the tailpipe

3.12
partial-flow opacimeter
instrument which samples a part of the total exhaust flow and passes the sample through the measuring chamber

3.13
opacimeter rise time
X
overall rise time of the instrument

Note 1 to entry: The definition of the term "opacimeter rise time" used in this document is equal to the definition of the term "opacimeter response time" used in ISO 11614.

3.14
opacimeter physical rise time
t_p
difference between the times when the raw k-signal reaches 10 % and 90 % of the full deviation when the *light absorption coefficient* (3.6) of the gas being measured is changed in less than 0,01 s

Note 1 to entry: The physical rise time of the *partial-flow opacimeter* (3.12) is defined with the sampling probe and transfer tube. Additional information on the physical rise time can be found in ISO 11614.

Note 2 to entry: The definition of the term “opacimeter physical rise time” used in this document is equal to the definition of the term “opacimeter physical response time” used in ISO 11614.

3.15
opacimeter electrical rise time
t_e
difference between the times when the instrument recorder output signal or display reaches 10 % and 90 % of full scale when the light source is interrupted or completely extinguished in less than 0,01 s

Note 1 to entry: Additional information on the electrical rise time can be found in ISO 11614.

Note 2 to entry: The definition of the term “opacimeter electrical rise time” used in this document is equal to the definition of the term “opacimeter electrical response time” used in ISO 11614.

3.16
filter rise time
t_F
filter rise time of the applied Bessel filter which is required to remove the high frequency distortions of the raw *opacity* (3.3) signal

Note 1 to entry: Additional information can be found in 9.2.

Note 2 to entry: The definition of the term “filter rise time” used in this document is equal to the definition of the term “filter response time” used in ISO 11614.

4 Symbols and abbreviated terms

4.1 Symbols

Symbol	Term	Unit
B	Bessel function constant	1
C	Bessel function constant	1
D	Bessel function constant	1
E	Bessel constant	1
f	Data sampling rate	Hz
f_a	Atmospheric factor	1
f_c	Bessel filter cut-off frequency	s^{-1}
k	Light absorption coefficient	m^{-1}
K	Bessel constant	1
L_A	Effective optical path length	m
L_{AS}	Standard effective optical path length	m
N	Opacity	%
N_A	Opacity at effective optical path length	%
N_{AS}	Opacity at standard effective optical path length	%
p_{me}	Brake mean effective pressure	kPa
p_S	Dry atmospheric pressure	kPa
P	Engine power	kW
S_j	Instantaneous smoke value	m^{-1} or %
t_e	Opacimeter electrical rise time	s
t_F	Filter rise time for Bessel function	s
t_p	Opacimeter physical rise time	s
Δt	Time between successive smoke data	s

Symbol	Term	Unit
T_a	Engine intake air temperature	°C
X	overall rise time	s
Y_j	Bessel averaged smoke value	m^{-1} or %
ρ	Dry ambient density	kg/m^3
τ	Transmittance	%
Ω	Bessel constant	1

4.2 Abbreviated terms

CL Collimating lens

EC Elemental Carbon

EP Exhaust pipe

FAT Free acceleration time

FM Flow monitoring device

ID Inner diameter

LD Light detector

LS Light source

LSV Lug smoke value

MC Measuring chamber

OD Outer diameter

OPL Optical path length

SPU Sampling pump

PSV Peak smoke value

PSV_a Average of peak smoke values

PSV_F Peak smoke value for free acceleration

SP Sampling probe

SSSV Steady-state smoke value

TS Temperature sensor

TT Transfer tube

5 Test conditions

For laboratory testing, the requirements regarding engine test conditions of ISO 8178-4 shall be applied except ISO 8178-4:—, 5.5.

For in-field testing the requirements for laboratory testing shall be applied with certain restrictions. Such restrictions shall be agreed in advance by the parties involved. It should be noted that emission tests carried out under different test conditions do not necessarily comply with the limits specified when using laboratory conditions.

6 Test fuels

Fuel characteristics influence the engine smoke emissions. Therefore, the characteristics of the fuel used for the test shall be determined, recorded and presented with the results of the test.

For laboratory testing, the characteristics of the fuel shall fulfil the requirements given in ISO 8178-4:—, Clause 6.

For in-field testing, the definitions for the acceptance test described in ISO 8178-4:—, Clause 6 shall apply. It should be noted that emission tests carried out using commercial fuel do not necessarily comply with the limits specified when using reference fuels.

7 Measurement equipment and accuracy

7.1 General

The following equipment shall be used for smoke tests on engines. This document refers to the equipment and accuracy requirements necessary for conducting a smoke test.

7.2 Engine and ambient related testing equipment

The following engine and ambient related testing equipment shall comply with the characteristics given in ISO 8178-1:—, Clause 6 and shall meet the calibration and verification requirements given in ISO 8178-1:—, Clause 9:

— dynamometer specifications;

— speed sensors;

— torque sensors;

— pressure transducers;

— temperature sensors;

— dew point sensors.

For in-field testing, where applicable, the requirements of the testing equipment shall be applied as described in ISO 8178-2.

7.3 Opacimeters

7.3.1 General

The smoke tests conforming with this document shall be conducted using opacimeter-type smoke meters. Three different types of opacimeters are allowed: in-line and end-of-line full-flow opacimeters and partial-flow opacimeters. Specifications for the three types of opacimeters can be found in Clause 10 and in ISO 11614:1999, Clauses 6 and 7.

7.3.2 Types of opacimeters

7.3.2.1 Partial-flow opacimeter

With the partial-flow opacimeter, a part of the exhaust is taken from the exhaust pipe and passed through a transfer line to the measuring chamber. With this type of opacimeter, the effective optical path length is a function of the opacimeter design.

7.3.2.2 Full-flow opacimeters

Two general types of full-flow opacimeters may be used, in-line and end-of-line.

With the in-line opacimeter, the opacity of the full exhaust gas within the exhaust pipe is measured. With this type of opacimeter, the effective optical path length is a function of the opacimeter design.

With the end-of-line opacimeter, the opacity of the full exhaust plume is measured as it exits the exhaust pipe. With this type of opacimeter, the effective optical path length is a function of the exhaust pipe design and the distance between the end of the exhaust pipe and the opacimeter.

7.3.3 Performance Specifications

7.3.3.1 Linearity

The difference between the value measured by the opacimeter and the reference value of the calibrating device shall not exceed ±2 % opacity.

7.3.3.2 Zero drift

Zero drift during a one-hour period shall not exceed ±0,5 % opacity.

7.3.3.3 Opacimeter display and range

For display in both opacity and light absorption coefficient the opacimeter shall have a measuring range appropriate for accurately measuring the smoke of the engine being tested. The resolution shall be at least 0,1 % of full scale.

The optical path length selected for the smoke instrument shall be suitable for the smoke levels being measured in order to minimize errors in calibrations, measurements and calculations.

7.3.3.4 Instrument rise time

The physical rise time of the opacimeter shall not exceed 0,2 s. The electrical rise time of the opacimeter shall not exceed 0,05 s.

7.3.3.5 Neutral density filters

Any neutral density filter used for calibrating and checking opacimeters shall be known to an accuracy of ±1 % opacity and the filter's nominal value shall be checked for accuracy at least yearly using a reference traceable to a national or International Standard.

Neutral density filters are precision devices and can easily be damaged during use. Handling should be minimized and, when required, should be done with care to avoid scratching or soiling of the filter.

7.3.4 Calibration of the opacimeter

7.3.4.1 Calibration procedure

The opacimeter shall be calibrated every 3 months.

The opacimeter shall be warmed up, stabilized and calibrated in accordance with the manufacturer's recommendations. If the opacimeter is equipped with a purge air system to prevent contamination of the instrument's optics, this system should also be activated and adjusted in accordance with the manufacturer's recommendations.

7.3.4.2 Linearity

With the opacimeter in the opacity readout mode and with no blockage of the opacimeter light beam, the readout shall be adjusted to 0 % ± 0,5 % opacity.

With the opacimeter in the opacity readout mode and all light prevented from reaching the receiver, the readout shall be adjusted to 100 % ± 0,5 % opacity.

The linearity of the opacimeter shall be checked in the opacity mode periodically in accordance with the manufacturer's recommendations. A neutral density filter between 10 % and 60 % opacity which meets the requirements of 7.3.3.5 shall be introduced to the opacimeter and the value recorded. The instrument readout shall not differ by more than ±2 % opacity from the nominal value of the neutral density filter.

8 Test run execution

8.1 Installation of the measuring equipment

8.1.1 General

The opacimeter and sample probes, if applicable, shall be installed after the muffler or any after-treatment device, if fitted, according to the installation procedures specified by the instrument manufacturer.

8.1.2 Exhaust pipe

For full-flow in-line opacimeters the exhaust pipe diameter shall be a straight pipe (free from elbows, bends and sudden change of pipe diameter) of at least 6 pipe diameters upstream and 3 pipe diameters downstream of the instrument location. If the diameter of the measuring zone is greater than the diameter of the exhaust pipe, a pipe gradually convergent before the measuring zone is required. Joints in the connecting pipes between the exhaust pipe and the opacimeter shall not allow air to enter from outside.

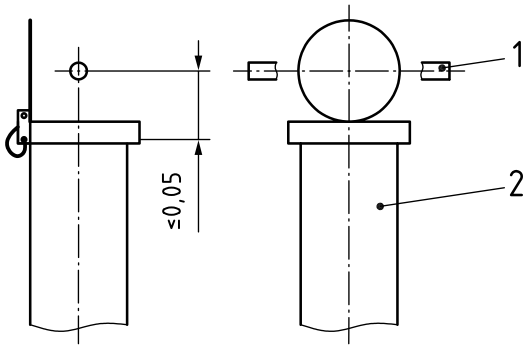
For full-flow end-of-line opacimeters the exhaust pipe diameter shall be a straight pipe (free from elbows, bends and sudden change of pipe diameter) of at least 6 pipe diameters upstream of the instrument location.

For partial-flow opacimeters, the exhaust pipe diameter shall be a straight pipe (free from elbows, bends and sudden change of pipe diameter) of at least 6 pipe diameters upstream and 3 pipe diameters downstream of the probe location. In the case of a large exhaust pipe (e.g. of more than about 250 mm diameter), it may be difficult to respect the requirements concerning the length of straight pipe. In such cases an alternative sampling arrangement may be used provided it has been established that the alternative ensures a representative sample.

8.1.3 Rain caps

Smoke measurements cannot be performed using a full-flow end-of-line opacimeter when a tailpipe rain cap is operational. If present, rain caps shall be removed or secured in the fully open position prior to smoke testing. If the opacimeter is installed without removing the rain cap, the meter shall be oriented so that the cap does not interfere with the smoke plume or block any portion of the opacimeter light beam (see Figure 1).

Dimension in metres



Key

1 full-flow opacimeter

2 tailpipe with raincap secured in fully open position; opacimeter oriented so that the light beam is not interrupted by open rain cap

Figure 1 — Rain cap

8.1.4 Field testing

Some machines have horizontal exhaust systems affixed to the underside of the chassis. Typically these exhaust systems have a curved tailpipe which directs the exhaust flow down against the surface of the earth.

Care should be exercised when using a full-flow end-of-line opacimeter with machines having this type of exhaust system. In some cases, exhaust gases can “rebound” off the earth and recirculate through the opacimeter light beam causing erroneously high smoke measurements. This condition can be aggravated if dust becomes entrained in the recirculating exhaust flow.

In most cases, little can be done to prevent this condition, however, it is recommended that testing personnel attempt to observe whether recirculation is occurring when testing machines with downward directed exhaust systems. If recirculation appears to be influencing the smoke measurement, the test results shall be considered unreliable (too high) and should be used with caution.

Some exhaust systems in the field are designed such that ambient air can enter the exhaust pipe and mix with the exhaust stream. Smoke measurement shall be made before this mixing occurs if field results are to be compared to the results of test bed measurements.

Accessibility to the exhaust system may be limited in some machines, and it may not be possible to install the instrumentation for field measurements in accordance with these recommendations. In these instances, smoke results may not be comparable to the test bed measurement results.

Excessively windy conditions shall be avoided when measuring in the field. Winds are considered excessive if they disturb the size, shape or location of the smoke plume in the region where the exhaust samples are drawn or where the smoke plume is measured. The effect of wind may be eliminated or reduced by locating the machine in a wind-sheltered area or by using measuring equipment designs which preclude wind effects on the smoke in the measuring or sampling zones.

No visible humidity (rain, fog or snow) shall be present in the region where exhaust samples are drawn or the smoke plume is measured. Care shall be taken to ensure that direct sunlight is not hitting the smoke plume or the receiver. Some equipment designs preclude the effects of these conditions.

8.2 Checking of the opacimeter

Prior to any zero and full-scale checks, the opacimeter shall be warmed up and stabilized in accordance with the instrument manufacturer’s recommendations. If the opacimeter is equipped with a purge air system to prevent contamination of the optics, this system shall also be activated and adjusted in accordance with the manufacturer's recommendations.

The zero and full-scale checks shall be made in the opacity readout mode, since the opacity scale offers two truly definable calibration points, namely 0 % opacity and 100 % opacity.

For test bed measurements with no blockage of the opacimeter light beam, the readout shall be adjusted to 0 % ± 0,5 % opacity. With the light being prevented from reaching the receiver, the readout shall be adjusted to 100 % ± 0,5 % opacity.

For field testing with no blockage of the opacimeter light beam, the readout shall be adjusted to 0 % ± 1 % opacity. With the light being prevented from reaching the receiver, the readout shall be adjusted to 100 % ± 1 % opacity.

Before testing, the instrument shall be returned to the *k* readout mode.

8.3 Test cycle

The engine shall be run on the applicable test cycle as described in Annex D, Annex E, Annex F and Annex G. Annex C provides further considerations to be taken into account.

9 Data evaluation and calculation

9.1 Data evaluation

9.1.1 General requirements — Opacimeters

The measured raw signal shall be converted into the respective smoke units and corrected for opacimeter optical path length differences, as necessary (see 9.1.2, 9.1.3 and 9.1.4). The smoke values shall be recorded using a minimum frequency of 20 Hz and reported in units of either opacity *N* or light absorption coefficient *k*. The smoke data shall then be processed by means of the Bessel algorithm, as described in 9.2. An example of the calculation procedure is given in Annex B.

The sample line length shall not affect the smoke trace. However, even though sample line length does not affect the shape of the smoke trace, it may introduce a delay between when the smoke is produced and when it is measured. The analysis of smoke traces shall account for any delay time associated with the transport of smoke in the exhaust system.

9.1.2 Beer-Lambert relationships

The Beer-Lambert law defines the relationship between transmittance, light absorption coefficient and effective optical path length as shown in Formula (3).

$$\frac{\tau}{100} = e^{-k \times L_A} \tag{3}$$

From the definitions of transmittance and opacity, the relationship between these parameters is defined as shown in Formula (4).

$$N = 100 - \tau \tag{4}$$

From Formulae (3) and (4) the following relationships are derived:

$$N_{AS} = 100 \times \left[1 - \left(1 - \frac{N_A}{100} \right)^{\frac{L_{AS}}{L_A}} \right] \tag{5}$$

$$k = -\frac{1}{L_A} \times \ln\left(1 - \frac{N_A}{100} \right) \tag{6}$$

9.1.3 Data conversion

Conversion from as-measured smoke values to appropriate reporting units is a two-step process. Since the basic measurement unit of all opacimeters is transmittance, the first step in all cases is to convert from transmittance τ to opacity at the as-measured effective optical path length N_A using Formula (4). For most opacimeters this step is done internally and is not apparent to the user. The second step of the process is to convert from N_A to the desired reporting units as follows.

If the test results are reported in opacity units, Formula (5) shall be used to convert from opacity at the as-measured effective optical path length N_A to opacity at the standard effective optical path length N_{AS}.

NOTE In the event that the measured and standard effective optical path lengths are identical, N_{AS} is equal to N_A, this secondary conversion step is not required.

If the test results are reported in units of light absorption coefficient, Formula (6) shall be applied.

9.1.4 Effective optical path length input values

In order to apply Formula (6), it is necessary to apply the as-measured effective optical path length (L_A). To use Formula (5), values shall be applied both for L_A and for the standard effective optical path length L_{AS}.

For full-flow end-of-line opacimeters, L_A is a function of the engine tailpipe design.

For partial-flow opacimeters and full-flow in-line opacimeters, L_A is a fixed function of the instrument measurement cell and purge air system design. Specification data supplied by the instrument manufacturer shall be used to determine the appropriate value for L_A when these types of opacimeters are used.

Typically, it is necessary to determine L_A to within ±0,002 m in order to achieve corrected smoke results that are accurate to within 2 % opacity.

Smoke opacity readings depend on the effective optical path length of the instrument. Since limit values may be established in units of percent opacity, they shall be referred to the standard effective optical path lengths (pipe diameter) at which the limit values apply. For meaningful smoke data comparisons, smoke opacity results shall be reported at the standard effective optical path lengths (L_{AS}) shown in Table 1.

For the purposes of Table 1 engine power does not need to be measured. Engine power is typically available either from a label on the engine, from the owner's manual of the engine, from the information used to apply for certification or type approval of the engine. In case that the engine power cannot be determined, it is not possible to evaluate the engine's compliance with limit values that are expressed in percent opacity.

Table 1 — Standard effective optical path lengths

Engine power P kW	Standard effective optical path length L_{AS} m
P < 37	0,038
37 ≤ P ≤ 75	0,05
75 ≤ P ≤ 130	0,075
130 ≤ P ≤ 225	0,1
225 ≤ P ≤ 450	0,125
P ≥ 450	0,15

9.2 Signal filter algorithm

9.2.1 General

The Bessel algorithm shall be used to calculate filtered values from the instantaneous smoke readings. The algorithm can be applied to either opacity or light absorption coefficient. The algorithm emulates a low pass second order filter, and its use requires iterative calculations to determine the coefficients. These coefficients are a function of the rise time of the opacimeter system and the sampling frequency of the unfiltered signal. Therefore, the calculations given in 9.2.2 shall be repeated whenever the system rise time and/or sampling frequency changes.

9.2.2 Calculation of filter rise time and Bessel constants

The required Bessel filter rise time t_F is a function of the physical and electrical rise times of the opacimeter system and the overall rise time X and shall be calculated using Formula (7):

$$t_F = \sqrt{X^2 - \left(t_p^2 + t_e^2\right)} \tag{7}$$

where

t_p is the physical rise time, expressed in seconds (s);

t_e is the electrical rise time, expressed in seconds (s);

t_F is the filter rise time, expressed in seconds (s);

X is the overall rise time, expressed in seconds (s).

Formula (7) can be used to adjust differing opacimeters to a common overall rise time provided that both t_p and t_e are much smaller than X.

The calculations for estimating the filter cut-off frequency (f_c) are based on a step input of 0 to 1 in <0,01 s (see Annex B). The rise time is defined as the time between when the Bessel output reaches 10 % (t_{10}) and when it reaches 90 % (t_{90}) of this step function. This shall be obtained by iterating on f_c until $t_{90} - t_{10} \cong t_F$. The first iteration for f_c is calculated using Formula (8).

$$f_c = \frac{\pi}{(10 \times t_F)} \tag{8}$$

The Bessel constants E and K shall be calculated using the Formulas (9) and (10).

$$E = \frac{1}{1 + \Omega \times \sqrt{3 \times D} + D \times \Omega^2} \tag{9}$$

$$K = 2 \times E \times \left(D \times \Omega^2 - 1 \right) - 1 \tag{10}$$

where

D equals 0,618 034;

Δt $= \frac{1}{f}$

Ω $= \frac{1}{\left[\tan\left(\pi \times \Delta t \times f_c \right) \right]}$.

Using the values of E and K, the Bessel filtered rise of X to a step input S_i shall be calculated as follows

$$Y_i = Y_{i-1} + E \times \left(S_i + 2 \times S_{i-1} + S_{i-2} - 4 \times Y_{i-2} \right) + K \times \left(Y_{i-1} - Y_{i-2} \right) \tag{11}$$

where

$S_{i-2} = S_{i-1} = 0$

$S_i = 1$

$Y_{i-2} = Y_{i-1} = 0$

The times t_{10} and t_{90} shall be interpolated. The difference in time between t_{90} and t_{10} defines the filter rise time t_F for that value of f_c. If this rise time is not close enough to the required rise time, iteration shall be continued until the actual rise time is within 1 % of the required rise as follows:

$$\left| \left(t_{90} - t_{10} \right) - t_F \right| \leq 0{,}01 \times t_F \tag{12}$$

An explanation of the Bessel filter, an example of the design of a Bessel algorithm, and an example of the calculation of the final smoke value are given in Annex B. The constants of the Bessel algorithm only depend on the design of the opacimeter and the sampling frequency of the data acquisition system. It is recommended that the opacimeter manufacturer provide the final Bessel filter constants for different sampling frequencies and that the user applies these constants for designing the Bessel algorithm and for calculating the smoke values.

9.2.3 Calculation of Bessel filtered smoke

Once the proper Bessel algorithm constants E and K have been calculated in accordance with 9.2.2, the Bessel algorithm shall then be applied to the instantaneous smoke trace using Formula (11).

The Bessel algorithm is recursive in nature. Thus it needs some initial input values of S_{i-1} and S_{i-2} and initial output values Y_{i-1} and Y_{i-2} to get the algorithm started. These may be assumed to be 0.

The resultant Bessel filtered smoke values are then used to calculate the appropriate smoke values as described in the applicable Annex.

9.3 Alternative signal handling

9.3.1 General

The Bessel filter algorithm described in 9.2 shall be used by default in this document. See Annex B for more details.

As an alternative to the Bessel filter algorithm, the specifications as given in 9.3.2 may be used for certain applications, if agreed upon by the parties involved. It should be noted that peak values determined during emission tests where different signal filter algorithms are applied will not necessarily be comparable.

9.3.2 Alternative specifications

The rise time of the electrical measuring circuit, being the time necessary for the indicating dial to reach 90 % of full-scale deflection on insertion of a screen fully obscuring the photoelectric cell, shall be 0,9 s to 1,1 s.

The damping of the electrical measuring circuit shall be such that the initial overswing beyond the final steady reading after any momentary variation in input (e.g. the calibration screen) does not exceed 4 % of that reading in linear scale units.

The rise time of the opacimeter which is due to physical phenomena in the smoke chamber is the time taken from the start of the gas entering the chamber to complete filling of the smoke chamber; it shall not exceed 0,4 s.

These provisions shall apply solely to opacimeters used to measure opacity under free acceleration.

In this document the overall rise time X is defined to be 1 s. State of the art opacimeters have a rise time (physical rise time t_p and electrical rise time t_e) much smaller than 1 s and so the Bessel Filter algorithm as described in 9.2 is applicable to achieve the overall rise time X of 1 s. For opacimeter designs, where the sum of t_p and t_e is more than 1 s, the alternative specifications may be allowed.

10 Opacimeter Design Specifications

10.1 General

10.2 and 10.4 and Figures 1 and 6 contain detailed descriptions of the full-flow and partial-flow opacimeter systems. Since various configurations can produce equivalent results, exact conformance with Figures 1 and 6 is not required. Additional components such as instruments, valves, solenoids, pumps and switches may be used to provide additional information and coordinate the functions of the component systems. Other components which are not needed to maintain the accuracy on some systems may be excluded if their exclusion is based upon good engineering judgement.

Full-flow and partial-flow opacimeters are based on the same measurement principle (exhaust gas opacity method based on light extinction). The decrease of light intensity between the light source and the receiver is caused by the exhaust gas components. The transmitted light through the specific optical path length with exhaust gas is measured at the receiver and compared with its original intensity (i.e. the intensity of the light source without the exhaust gas components).

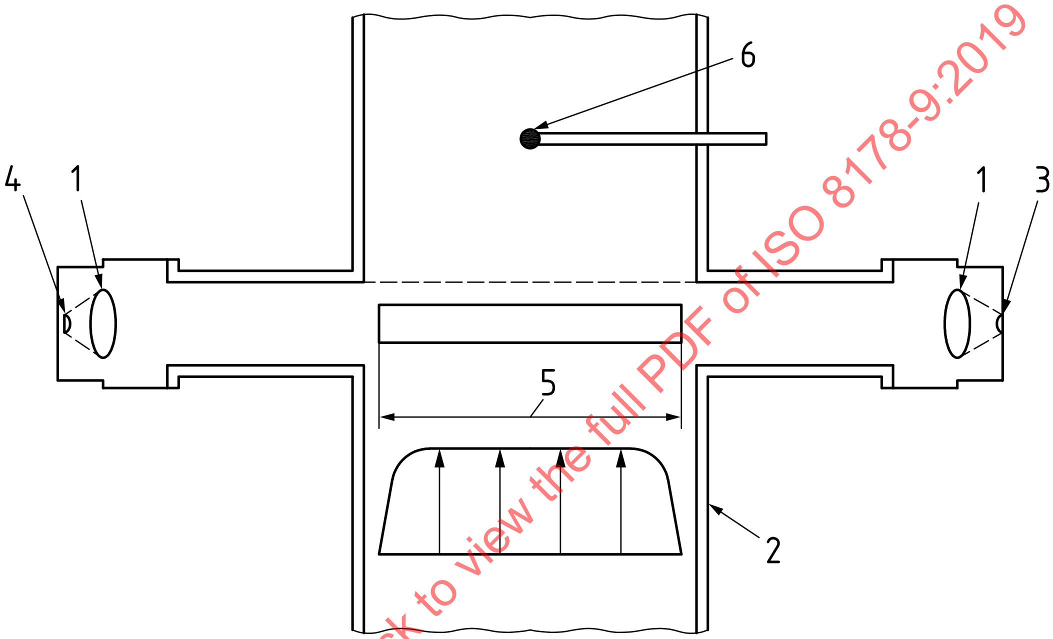
The smoke measurement depends upon the design of the instrument and may be carried out in the exhaust pipe (full-flow in-line opacimeter), at the end of the exhaust pipe (full-flow end-of-line opacimeter) or by taking a sample from the exhaust (partial-flow opacimeter).

10.2 Full-flow opacimeter

10.2.1 General

With the in-line opacimeter (see Figure 2), the opacity of the full exhaust plume within the exhaust pipe is measured. With this type of opacimeter, the effective optical path length is a function of the opacimeter design.

With the end-of-line opacimeter, the opacity of the full exhaust plume is measured as it exits the exhaust pipe. With this type of opacimeter, the effective optical path length is a function of the exhaust pipe design and the distance between the end of the exhaust pipe and the opacimeter.



Key

1 collimating lens
2 exhaust pipe
3 light detector
4 light source
5 optical path length
6 temperature sensor (optional)

Figure 2 — Full-flow opacimeter

10.2.2 Components of a full-flow opacimeter

10.2.2.1 Light source (LS)

The light source shall be an incandescent lamp with a color temperature in the range of 2 800 K to 3 250 K or a green light emitting diode (LED) with a spectral peak between 550 nm and 570 nm. The light source shall be protected against contamination by means that do not influence the optical path length beyond the manufacturer's specifications.

10.2.2.2 Light detector (LD)

The detector shall be a photocell or a photodiode (with a filter, if necessary). In the case of an incandescent light source, the receiver shall have a peak spectral response similar to the phototopic curve of the human eye (maximum response) in the range of 550 nm to 570 nm, to less than 4 % of that maximum response below 430 nm and above 680 nm. The light detector shall be protected against contamination by means that do not influence the optical path length beyond the manufacturer's specifications.

10.2.2.3 Collimating lens (CL)

The light output shall be collimated to a beam with a maximum diameter of 30 mm. The rays of the light beam shall be parallel within a tolerance of 3° of the optical axis.

10.2.2.4 Temperature sensor (TS)

Optional for monitoring the exhaust gas temperature during the test.

10.2.2.5 Optical path length (OPL)

The length of the smoke-obscured optical path between the opacimeter light source and the receiver, corrected as necessary for non-uniformity due to density gradients and fringe effect. The optical path length shall be submitted by the instrument manufacturer taking into account any measures against contamination (e.g. purge air). If the optical path length is not available, it shall be determined in accordance with ISO 11614:1999, 11.6.5. For the correct determination of the optical path length, a minimum exhaust gas velocity of 20 m/s is required.

10.3 Determination of effective optical path length (L_A)

10.3.1 General

Portions of the light source to receiver path length which are not smoke obscured do not contribute to the effective optical path length. If the opacimeter's light beam is located sufficiently close to the exhaust outlet (within 0,07 m), the cross section of the smoke plume as it passes by the opacimeter is essentially the same as the tailpipe outlet along the line of orientation of the opacimeter light beam. In general, this distance should be determined by direct measurement of the tailpipe outlet. To achieve corrected smoke results which are accurate within ±2 % opacity, determination of L_A shall be made within ±6 %. (The largest error in opacity occurs at an opacity of approximately 60 %. At lower and higher values of opacity, less accurate determination of L_A can be tolerated if agreed by the parties involved.) For the smallest standard effective optical path length (0,038 m), ±6 % equates to an accuracy of ±0,002 m.

It is often difficult, particularly in field testing, to gain access to and obtain direct measurements of the tailpipe outlets on many machines. Therefore, the extension of the exhaust stack pipe from three to a maximum of 30 times the stack pipe diameter should be considered if the engine manufacturer does not have any objections. Proper sealing of that joint is necessary to avoid exhaust dilution with air.

For many common tailpipe designs L_A can be determined with sufficient accuracy from external exhaust system dimensions which are easier to measure. The remainder of this clause describes these cases and the principles and procedures that shall be considered in determining L_A.

10.3.2 External versus internal tailpipe dimensions

10.3.2.1 General

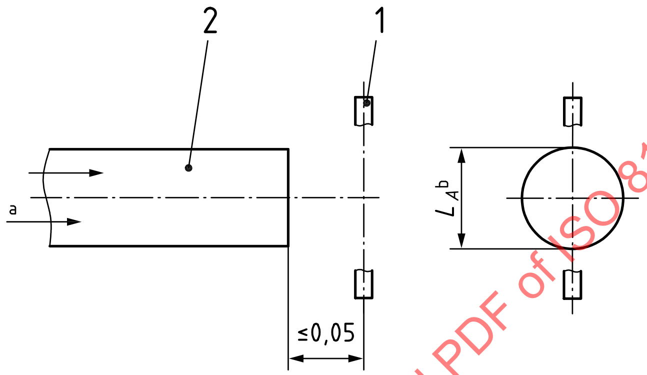
Most tailpipes encountered on machines are constructed from metal tubing of various standard nominal sizes. Nominal tubing sizes are based on the tubing OD whereas it is the internal dimension of the tailpipe that dictates L_A. The difference between the external and internal tailpipe dimension is twice the tubing wall thickness, which is typically small.

Use of the external tailpipe dimension as the as-measured effective optical path length results in corrected smoke values which are slightly less than the true corrected smoke values (<1 % opacity). In most cases, this small error is acceptable. However, in cases where extreme accuracy is required or where the tailpipe wall thickness is unusually large, the material thickness should be accounted for in determining L_A.

10.3.2.2 Straight circular non-bevelled tailpipes

This is the simplest tailpipe design that may be encountered and is illustrated in Figure 3. In this case, the opacimeter's light beam shall be oriented such that it is perpendicular to and passes through the central axis of the smoke plume and is within 0,05 m of the tailpipe exit. If these guidelines are followed, L_A is equal to the tailpipe ID and can usually be adequately approximated by the tailpipe OD (see 10.3.2.1).

Dimension in metres



Key

1 full-flow opacimeter

2 circular tailpipe

a Exhaust flow.

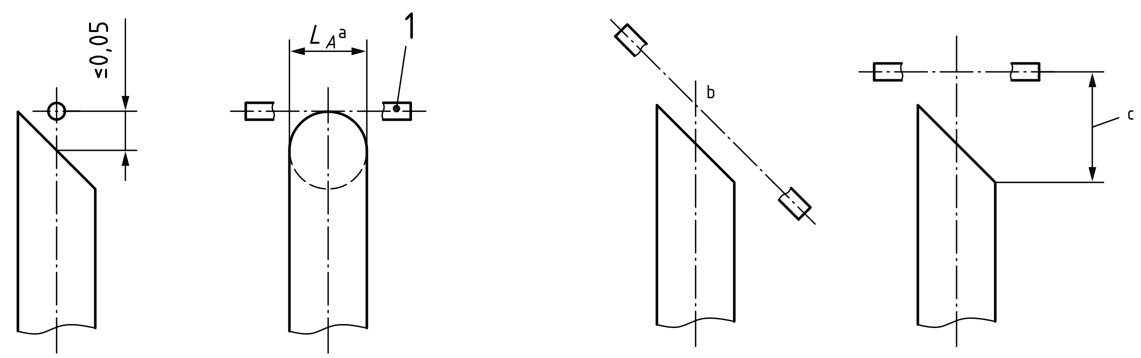
b L_A = Tailpipe inner diameter; L_A = Tailpipe outer diameter for wall thickness less than 1,5 mm.

Figure 3 — Straight circular non-bevelled tailpipe

10.3.2.3 Straight circular bevelled tailpipes

A bevelled tailpipe is formed when the outlet of the tailpipe is not cut off square (perpendicular) to the axis of the exhaust flow. When this type of tailpipe is encountered, there is only one recommended opacimeter mounting orientation. The axis of the opacimeter's light beam shall be perpendicular to and passing through the central axis of the smoke plume and should be parallel to the minor axis of the elliptical shape to the tailpipe exit. The opacimeter's light beam shall also be within 0,05 m of the tailpipe outlet (see Figure 4). If these guidelines are followed, L_A is equal to the tailpipe ID and can usually be adequately approximated by the tailpipe OD (see 10.3.2.1).

Dimension in metres



a) Proper opacimeter orientation **b) Improper opacimeter orientation**

Key

1 full-flow opacimeter

a L_A = Tailpipe ID; L_A = Tailpipe OD for wall thickness less than 1,5 mm.

b Light beam not perpendicular to exhaust flow.

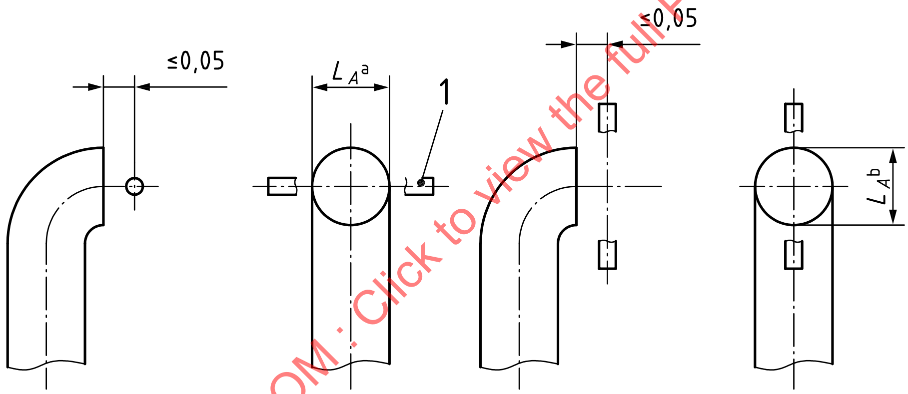
c Typically > 0,05 m.

Figure 4 — Straight circular bevelled tailpipe

10.3.2.4 Curved circular tailpipes

When the central axis of the tailpipe is curved at the approach to the exit, the tailpipe is said to be curved and the cross section of the tailpipe outlet is non-circular. To avoid erroneously low readings when this type of tailpipe is encountered, the opacimeter shall be mounted such that the axis of the opacimeter's light beam is perpendicular to and passing through the central axis of the smoke plume (not necessarily the centerline of the pipe) and is parallel to the minor axis of the tailpipe exit. The opacimeter light beam shall also be within 0,05 m of the tailpipe exit (see Figure 5). If these guidelines are followed, L_A is equal to the tailpipe ID and can usually be adequately approximated by the tailpipe OD (see 10.3.2.1). Opacimeter orientations in which the opacimeter's light beam is not parallel to the minor axis of the tailpipe exit may be used, but in these cases it will be necessary to determine L_A by direct measurement.

Dimension in metres



Key

1 full-flow opacimeter

a L_A = Minor axis of outlet; L_A = Tailpipe ID; L_A = Tailpipe OD for wall thickness less than 1,5 mm.

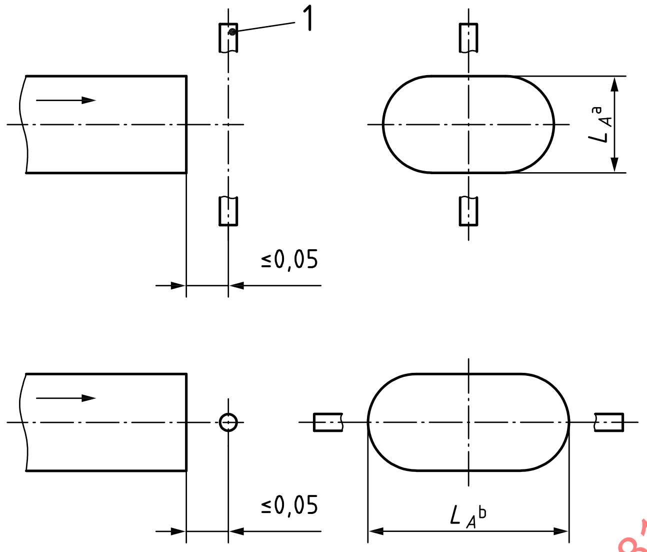
b L_A = Minor axis of outlet; L_A > Tailpipe ID (to be determined by direct measurement).

Figure 5 — Curved circular tailpipe (proper opacimeter orientations)

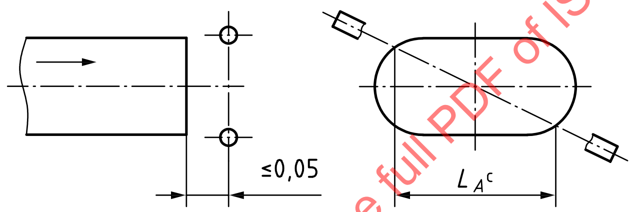
10.3.2.5 Non-circular tailpipe

If the tailpipe cross section is non-circular, the opacimeter shall be mounted such that the opacimeter's light beam is perpendicular to and passes through the central axis of the smoke plume and is within 0,05 m of the tailpipe exit.

For these cases, L_A shall be determined by direct measurement. If the tailpipe cross section is an oval or an ellipse, the opacimeter's light beam has to be aligned with either the major or minor axis of the tailpipe cross section in order to facilitate the measurement of L_A (see Figure 6).



a) Proper opacimeter orientation



b) Improper opacimeter orientation

Key

1 full-flow opacimeter

a L_A = Minor axis to be determined by direct measurement.

b L_A = Major axis to be determined by direct measurement.

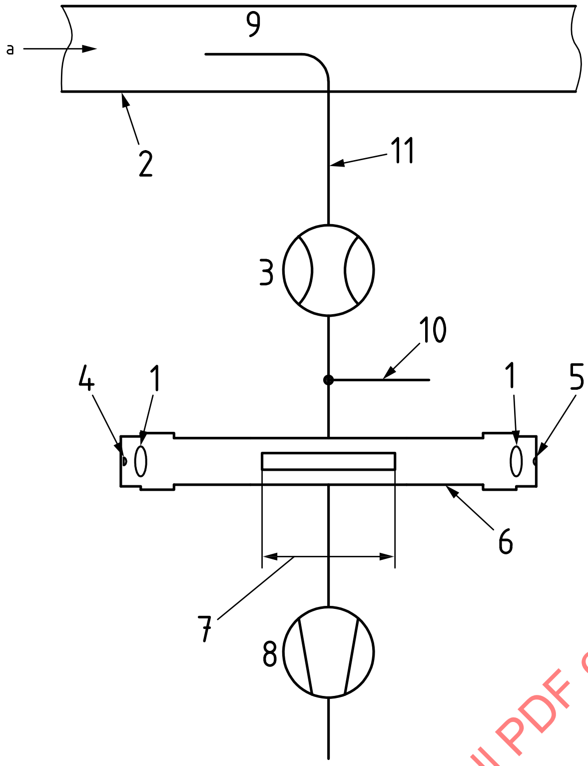
c L_A = Major or minor axis difficult to measure.

Figure 6 — Non-circular tailpipe

10.4 Partial-flow-opacimeter

10.4.1 General

With the partial-flow opacimeter (see Figure 7), part of the exhaust is taken from the exhaust pipe and passed through a transfer line to the measuring chamber. With this type of opacimeter, the effective optical path length is a function of the opacimeter design. The rise times referred to in 9.2.2 apply to the minimum flow rate of the opacimeter, as specified by the instrument manufacturer.



Key

1 collimating lens
2 exhaust pipe
3 flow monitoring device
4 light detector
5 light source
6 measuring chamber
7 optical path length
8 sampling pump (optional)
9 sample probe
10 temperature sensor
11 transfer tube
a Exhaust.

Figure 7 — Partial-flow opacimeter

10.4.2 Components of partial-flow opacimeter

10.4.2.1 Sampling probe (SP)

The sampling probe shall be placed in the exhaust gas flow to obtain a representative sample of the exhaust gas.

The sampling probe shall be an open tube facing upstream and placed in the exhaust pipe centerline. The clearance with the wall of the tailpipe shall be at least 5 mm. The probe diameter shall ensure a representative sampling and a sufficient flow through the opacimeter.

The sampling probe shall be gastight with no sharp bends or constrictions which might cause avoidable local resistance to the gas flow.

10.4.2.2 Transfer tube (TT)

The transfer tube shall be inclined upwards from the sampling point to the opacimeter and shall be gastight with no sharp bends or constrictions which might cause avoidable local resistance to the gas flow. In order to provide the required temperature conditions at the chamber inlet, the transfer tube may be conditioned (heated) but this must not unduly modify the gas characteristics. The transfer tube shall:

— be as short as possible and ensure an exhaust gas temperature of 100 °C ± 30 °C (373 K ± 30 K) at the entrance to the measuring chamber;

— have a wall temperature sufficiently above the dew point of the exhaust gas to prevent condensation;

— be equal to the diameter of the sampling probe over the entire length;

— have a response time which is part of the physical rise time t_p of less than 0,05 s at minimum instrument flows;

— have no significant effect on the smoke peak.

10.4.2.3 Flow monitoring device (FM)

Flow monitoring to detect the correct flow into the measuring chamber. The minimum and maximum flow rates shall be specified by the instrument manufacturer and shall be such that the rise time requirement of the instrument and the optical path length specifications are met. The flow monitoring device may be close to the sampling pump (SPU), if used.

10.4.2.4 Measuring chamber (MC)

The measuring chamber shall have a non-reflective internal surface or equivalent optical environment. The impingement of stray light on the detector due to internal reflections of diffusion effects shall be reduced to a minimum.

The pressure of the gas in the measuring chamber shall not differ from the atmospheric pressure by more than 0,75 kPa. Where this is not possible by design, the opacimeter reading shall be converted to atmospheric pressure.

The wall temperature of the measuring chamber shall be set to within ±5 °C between 70 °C (343 K) and 100 °C (373 K), but in all cases sufficiently above the dew point of the exhaust gas to prevent condensation. The measuring chamber shall be equipped with appropriate sensors for measuring the temperature.

10.4.2.5 Optical path length (OPL)

The length of the smoke-obscured optical path between the opacimeter light source and the receiver, corrected as necessary for non-uniformity due to density gradients and fringe effect. The optical path length shall be submitted by the instrument manufacturer taking into account any measures against contamination (e.g. purge air).

10.4.2.6 Light source (LS)

The light source shall be an incandescent lamp with a color temperature in the range of 2 800 K to 3 250 K or a green light emitting diode (LED) with a spectral peak between 550 nm and 570 nm. The light source shall be protected against contamination by means that do not influence the optical path length beyond the manufacturer's specifications.

10.4.2.7 Light detector (LD)

The detector shall be a photocell or a photodiode (with a filter, if necessary). In the case of an incandescent light source, the receiver shall have a peak spectral response similar to the phototopic curve of the human eye (maximum response) in the range of 550 nm to 570 nm, to less than 4 % of that maximum response below 430 nm and above 680 nm. The light detector shall be protected against contamination by means that do not influence the optical path length beyond the manufacturer's specifications.

10.4.2.8 Collimating lens (CL)

The light output shall be collimated to a beam with a maximum diameter of 30 mm. The rays of the light beam shall be parallel within a tolerance of 3° of the optical axis.

10.4.2.9 Temperature sensor (TS)

For monitoring the exhaust gas temperature at the entrance to the measuring chamber.

10.4.2.10 Sampling pump (SPU)

Optionally, a sampling pump downstream of the measuring chamber may be used to transfer the sample gas through the measuring chamber.

Annex A
(informative)

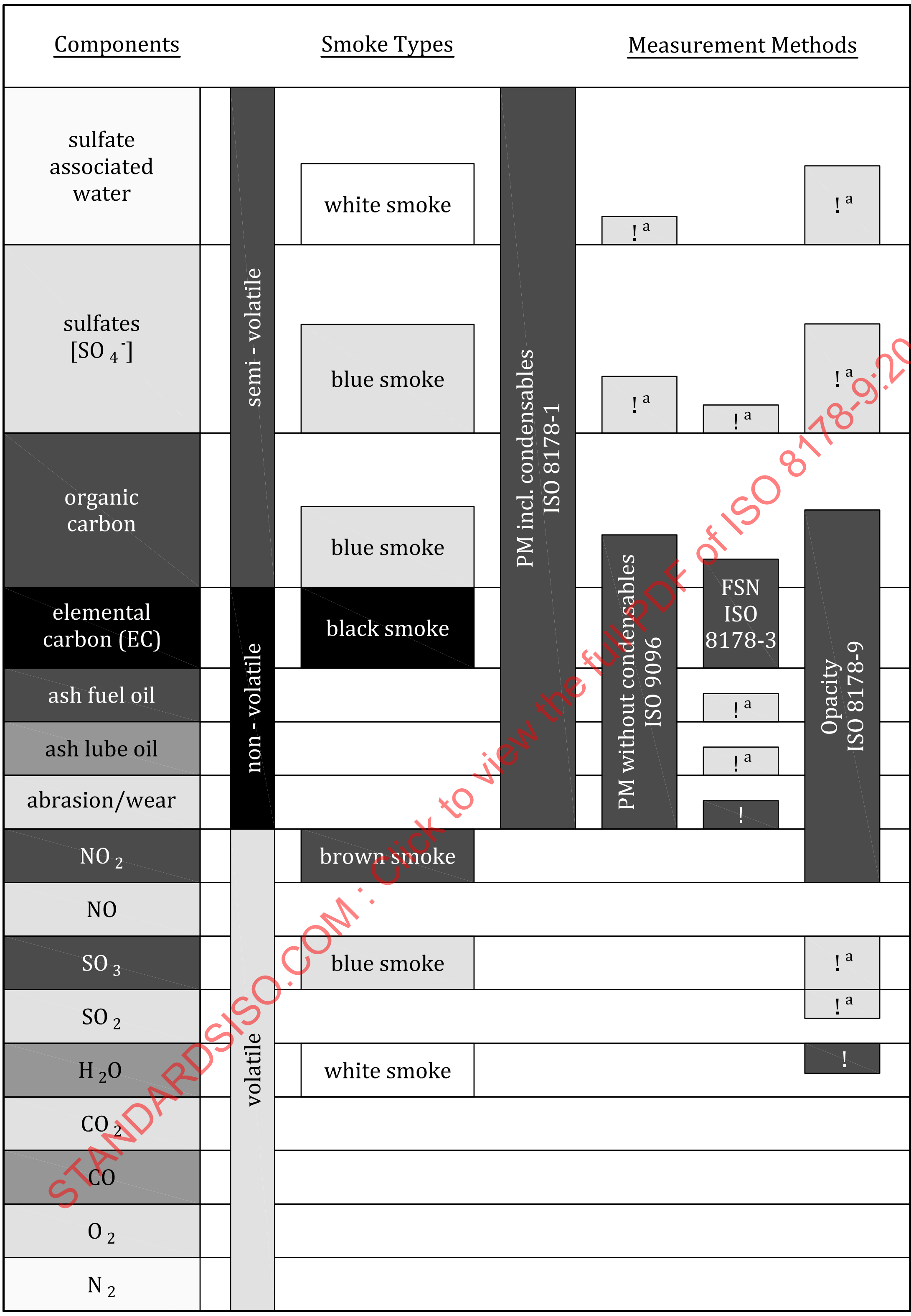
Overview particulate and soot measurement methods

In much of the scientific literature the terms soot, black smoke, black carbon (BC) and elemental carbon (EC) are used interchangeably, although soot, black smoke, BC and EC commonly have operational and source-based definitions, respectively, notwithstanding that reliable reference samples and aerosol standards do not exist for either one.

ISO 8178-1 describes test bed measurement of gaseous and particulate exhaust emissions which includes the measurement of particulate mass and particle number emissions.

ISO 8178-3 describes test procedures for measurement of exhaust gas smoke emissions from compression ignition engines using a filter-type smoke meter.

This document describes test cycles and test procedures for measurement of exhaust gas smoke emissions from compression ignition engines using an opacimeter.



Key

! Contribution possible.

[a] Contribution can be minimized or even eliminated by use of appropriate fuel and lube oil.

NOTE Particle number and its measurement methods are not included in the figure. For more information refer to ISO 8178-1.

Figure A.1 — Exhaust components and measurement methods

Annex B
(informative)

Example of calculation procedure

B.1 General

Since the application of the Bessel algorithm on filtering is an averaging procedure in smoke determination, an explanation of the Bessel filter, an example of the design of a Bessel algorithm and an example of the calculation of the final smoke value are given in this annex.

The constants of the Bessel algorithm depend on the design of the opacimeter and on the sampling frequency of the data acquisition system. It is recommended that the opacimeter manufacturer provides the final Bessel filter constants for different sampling rates and that the customer use these constants for designing the Bessel algorithm and for calculating the smoke values.

B.2 General remarks on the Bessel filter

Due to high frequency distortions, the raw opacity signal usually shows a highly scattered trace. To remove these high frequency distortions a Bessel filter is required for the smoke test. The Bessel filter itself is a recursive, second-order low-pass filter which guarantees the fastest signal rise without overshoot.

Assuming a real time raw exhaust plume in the exhaust pipe, each opacimeter shows a delayed and differently measured opacity trace. The delay and the magnitude of the measured opacity trace is primarily dependent on the geometry of the measuring chamber of the opacimeter, including the exhaust sample lines, and on the time needed for processing the signal in the electronics of the opacimeter. The values that characterize these two effects are called the physical and the electrical rise time which represent an individual filter for each type of opacimeter. The goal of applying a Bessel filter is to guarantee a uniform overall filter characteristic of the whole opacimeter system, consisting of

— physical rise time of the opacimeter (t_p);

— electrical rise time of the opacimeter (t_e);

— filter rise time of the applied Bessel filter (t_F).

The resulting overall rise time of the system (X) is given by

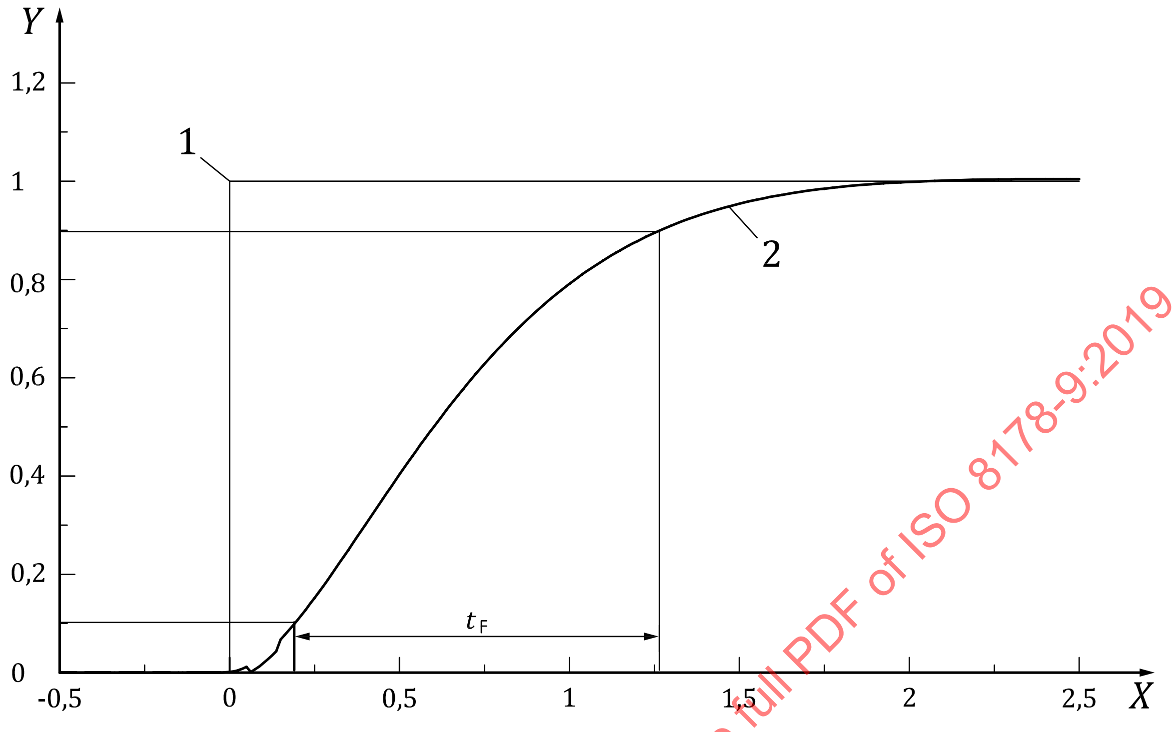
$$X = \sqrt{t_F^2 + t_p^2 + t_e^2} \tag{B.1}$$

and shall be equal for all kinds of opacimeters in order to give the same smoke value. Therefore, a Bessel filter shall be created in such a way, that the filter rise time (t_F) together with the physical rise time (t_p) and electrical rise time (t_e) of the individual opacimeter shall result in the required overall rise time (X). Since t_p and t_e are given values for each individual opacimeter, and X is defined to be 1 s in this document, t_F can be calculated as follows:

$$t_F = \sqrt{X^2 - t_p^2 - t_e^2} \tag{B.2}$$

By definition, the filter rise time t_F is the rise time of a filtered output signal between 10 % and 90 % on a step input signal. Therefore the cut-off frequency of the Bessel filter shall be iterated in such a way that the rise time of the Bessel filter fits into the required rise time.

In Figure B.1, the traces of a step input signal and Bessel filtered output signal as well as the rise time of the Bessel filter (t_F) are shown.



Key

Y signal

X time, expressed in seconds (s)

1 step input signal

2 Bessel filtered output signal

Figure B.1 — Traces of a step input signal and the filtered output signal

B.3 Calculation of the Bessel algorithm

B.3.1 General

Designing the final Bessel filter algorithm is a multi-step process which requires several iteration cycles. The scheme of the iteration procedure, which is based upon Clause 10, is shown in Figure B.2.

In the following example, a Bessel algorithm is designed for the peak smoke value (PSV) in several steps according to the iteration procedure shown in Figure B.2. For the PSV, the overall rise time is defined as 1 s. The iteration procedure for LSV is identical.

For the opacimeter and the data acquisition system, the following characteristics are assumed:

Physical rise time t_p:	0,15 s
Electrical rise time t_e:	0,05 s
Overall rise time *X*:	1 s (by definition for PSV)
Sampling frequency:	150 Hz

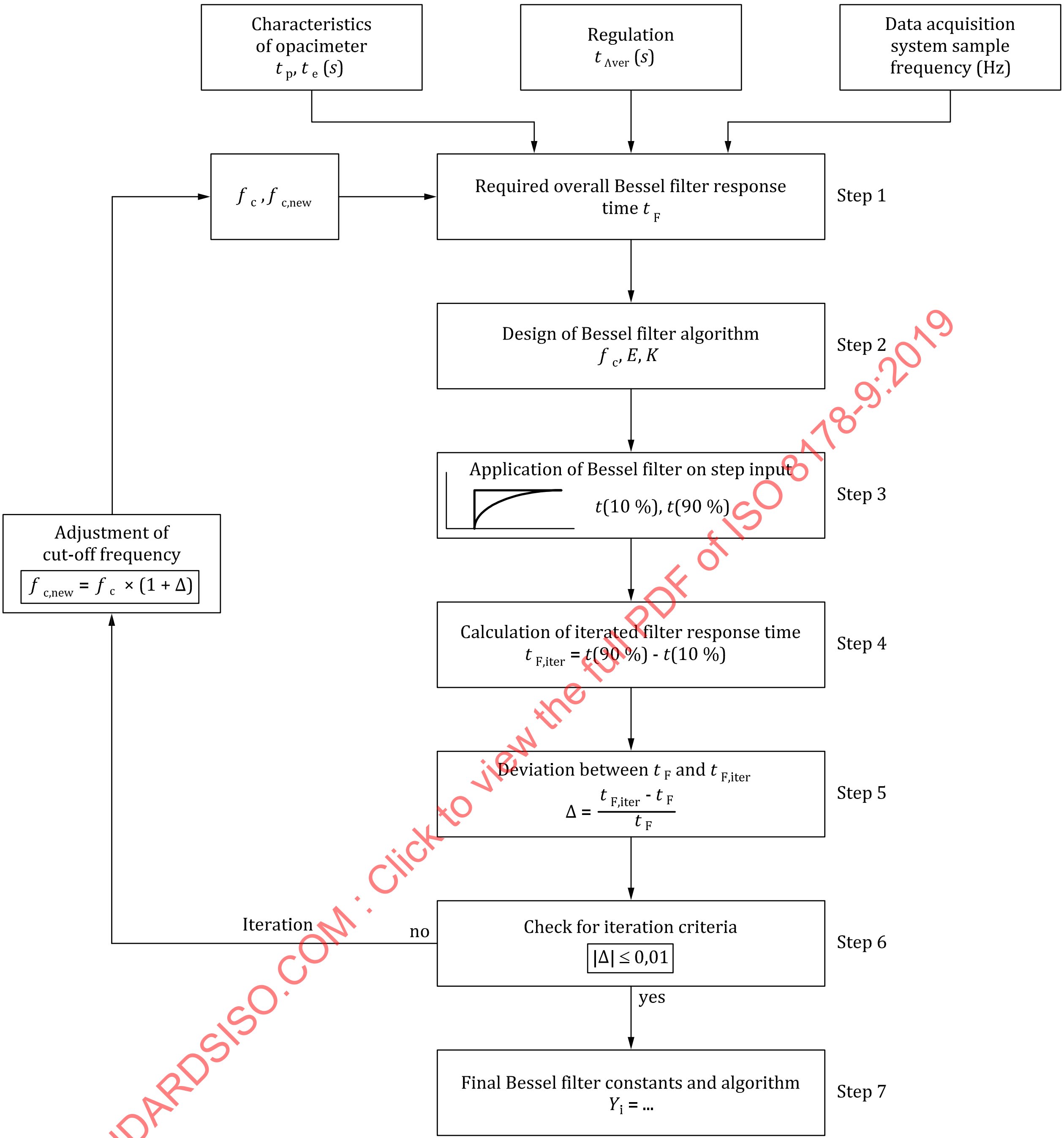


Figure B.2 — Iteration scheme of Bessel filter algorithm

B.3.2 Step 1: Required Bessel filter rise time t_F

$$t_F = \sqrt{X^2 - (t_p^2 + t_e^2)} \tag{B.3}$$

$$t_F = \sqrt{1^2 - (0{,}15^2 + 0{,}05^2)} = 0{,}987\,421\ \text{s} \tag{B.4}$$

B.3.3 Step 2: Estimation of cut-off frequency, f_c, and calculation of Bessel constants E and K for first iteration

$$f_{\mathrm{c}} = \pi / (10 \times t_{\mathrm{F}}) \tag{B.5}$$

$$f_{\mathrm{c}} = \pi / (10 \times 0{,}987\,421) = 0{,}318\,161 \text{ Hz} \tag{B.6}$$

$$\Delta t = 1/150 \tag{B.7}$$

$$\Omega = 1/\tan(\pi \times \Delta t \times f_{\mathrm{c}}) \tag{B.8}$$

$$\Omega = 1/\tan(\pi \times 1/150 \times 0{,}318\,161) = 150{,}067\,975 \tag{B.9}$$

$$E = \frac{1}{1 + \Omega \times \sqrt{3 \times D} + D \times \Omega^2} \tag{B.10}$$

$$D = 0{,}618\,034 \tag{B.11}$$

$$E = \frac{1}{1 + 150{,}067\,975 \times \sqrt{3 \times 0{,}618\,034} + 0{,}618\,034 \times 150{,}067\,975^2} = 7{,}080\,29 \times 10^{-5} \tag{B.12}$$

$$K = 2 \times E \times \left(D \times \Omega^2 - 1\right) - 1 \tag{B.13}$$

$$K = 2 \times 7{,}080\,29 \times 10^{-5} \times (0{,}618\,034 \times 150{,}067\,975\,2 - 1) - 1 = 0{,}970\,781 \tag{B.14}$$

This gives the Bessel algorithm:

$$Y_i = Y_{i-1} + E \times (S_i + 2 \times S_{i-1} + S_{i-2} - 4 \times Y_{i-2}) + K \times (Y_{i-1} - Y_{i-2}) \tag{B.15}$$

$$Y_i = Y_{i-1} + 7{,}080\,29 \times 10^{-5} \times (S_i + 2 \times S_{i-1} + S_{i-2} - 4 \times Y_{i-2}) + 0{,}970\,781 \times (Y_{i-1} - Y_{i-2}) \tag{B.16}$$

where

S_i represents the values of the step input signal (either “0” or “1”);

Y_i represents the filtered values of the output signal.

B.3.4 Step 3: Application of Bessel filter on step input

The Bessel filter rise time t_F is defined as the rise time of the filtered output signal between 10 % and 90 % on a step input signal. For determining the times of 10 % (t_{10}) and 90 % (t_{90}) of the output signal, a Bessel filter shall be applied to a step input using the above values of f_c, E and K.

The index numbers, the time and the values of a step input signal and the resulting values of the filtered output signal for the first and the second iteration are shown in Table B.1. The points adjacent to t_{10} and t_{90} are marked in boldface.

Table B.1 — Iteration scheme of Bessel filter algorithm

Index	Time	Step input signal	Filtered output signal	
	s	S_i	Y_i	
			1st iteration	2nd iteration
−2	−0,013 333	0	0,000 000	0,000 000
−1	−0,006 667	0	0,000 000	0,000 000
0	0,000 000	1	0,000 071	0,000 084
1	0,006 667	1	0,000 352	0,000 416
2	0,013 333	1	0,000 908	0,001 074
3	0,020 000	1	0,001 731	0,002 046
4	0,026 667	1	0,002 813	0,003 321
5	0,033 333	1	0,004 146	0,004 891
24	0,160 000	1	0,067 884	0,078 788
25	0,166 667	1	0,072 823	0,084 448
26	0,173 333	1	0,077 882	0,090 237
27	0,180 000	1	0,083 056	**0,096 149**
28	0,186 667	1	0,088 339	**0,102 178**
29	0,193 333	1	0,093 728	0,108 318
30	0,200 000	1	**0,099 218**	0,114 564
31	0,206 667	1	**0,104 804**	0,120 911
32	0,213 333	1	0,110 482	0,127 352
33	0,220 000	1	0,116 248	0,133 884
34	0,226 667	1	0,122 097	0,140 500
35	0,233 333	1	0,128 025	0,147 197
36	0,240 000	1	0,134 029	0,153 969
37	0,246 667	1	0,140 104	0,160 811

Table B.1 *(continued)*

Index	Time	Step input signal	Filtered output signal	
	s	S_i	Y_i	
			1st iteration	2nd iteration
174	1,160 000	1	0,859 856	0,896 087
175	1,166 667	1	0,862 443	**0,898 336**
176	1,173 333	1	0,864 994	**0,900 548**
177	1,180 000	1	0,867 510	0,902 723
178	1,186 667	1	0,869 990	0,904 863
179	1,193 333	1	0,872 436	0,906 967
180	1,200 000	1	0,874 846	0,909 036
181	1,206 667	1	0,877 223	0,911 071
182	1,213 333	1	0,879 565	0,913 072
183	1,220 000	1	0,881 874	0,915 038
184	1,226 667	1	0,884 149	0,916 972
185	1,233 333	1	0,886 392	0,918 872
186	1,240 000	1	0,888 601	0,920 740
187	1,246 667	1	0,890 779	0,922 575
188	1,253 333	1	0,892 924	0,924 379
189	1,260 000	1	0,895 037	0,926 151
190	1,266 667	1	0,897 120	0,927 893
191	1,273 333	1	**0,899 170**	0,929 603
192	1,280 000	1	**0,901 191**	0,931 284
193	1,286 667	1	0,903 180	0,932 934
194	1,293 333	1	0,905 140	0,934 556

In Table B.1, first iteration, the 10 % value occurs between index number 30 and 31 and the 90 % value occurs between index numbers 191 and 192. For the calculation of $t_{\mathrm{F,iter}}$ the exact t_{10} and t_{90} values are determined by linear interpolation between the adjacent measuring points, as follows:

$$t_{10} = t_{\mathrm{lower}} + \Delta t \times \left(0{,}1 - out_{\mathrm{lower}}\right) / \left(out_{\mathrm{upper}} - out_{\mathrm{lower}}\right) \tag{B.17}$$

$$t_{90} = t_{\mathrm{lower}} + \Delta t \times \left(0{,}9 - out_{\mathrm{lower}}\right) / \left(out_{\mathrm{upper}} - out_{\mathrm{lower}}\right) \tag{B.18}$$

Where out_{upper} and out_{lower}, respectively, are the adjacent points of the Bessel filtered output signal, and t_{lower} is the time of the adjacent time point, as indicated in Table B.1.

$$t_{10} = 0{,}200\,000 + 0{,}006\,667 \times \left(0{,}1 - 0{,}099\,218\right) / \left(0{,}104\,804 - 0{,}099\,218\right) = 0{,}200\,933\ \mathrm{s} \tag{B.19}$$

$$t_{90} = 1{,}273\,333 + 0{,}006\,667 \times \left(0{,}9 - 0{,}899\,170\right) / \left(0{,}901\,191 - 0{,}899\,170\right) = 1{,}276\,071\ \mathrm{s} \tag{B.20}$$

B.3.5 Step 4: Filter rise time of first iteration cycle $t_{\mathrm{F,iter}}$

$$t_{\mathrm{F,iter}} = t_{90} - t_{10} \tag{B.21}$$

$$t_{\mathrm{F,iter}} = 1{,}276\,071 - 0{,}200\,933 = 1{,}075\,138\ \mathrm{s} \tag{B.22}$$

B.3.6 Step 5: Deviation between required and obtained filter rise time, Δ, of first iteration cycle

$$\Delta = \left(t_{\mathrm{F,iter}} - t_{\mathrm{F}}\right) / t_{\mathrm{F}} \tag{B.23}$$

$$\Delta = \left(1{,}075\,138 - 0{,}987\,421\right) / \left(0{,}987\,421\right) = 0{,}088\,834 \tag{B.24}$$

B.3.7 Step 6: Checking the iteration criteria

$|\Delta| = 0{,}01$ is required. Since 0,088 834 > 0,01, the iteration criteria are not met and a further iteration cycle shall be started. For this iteration cycle, a new cut-off frequency is calculated from f_c and Δ as follows:

$$f_{\mathrm{c,new}} = f_{\mathrm{c}} \times \left(1 + \Delta\right) \tag{B.25}$$

$$f_{\mathrm{c,new}} = 0{,}318\,161 \times \left(1 + 0{,}088\,834\right) = 0{,}346\,425\ \mathrm{Hz} \tag{B.26}$$

This new cut-off frequency is used in the second iteration cycle, starting again at Step 2. The iteration shall be repeated until the iteration criteria are met. The resulting values of the first and second iteration are given in Table B.2.

Table B.2 — Values of the first and second iterations

Parameter	Unit	1st iteration	2nd iteration
f_c	Hz	0,318 161	0,346 425
E	1	7,080 29 × 10^{-5}	8,383 292 × 10^{-5}
K	1	0,970 781	0,968 199
t_{10}	s	0,200 933	0,184 259
t_{90}	s	1,276 071	1,178 348
$t_{\mathrm{F,iter}}$	s	1,075 138	0,994 090
Δ	1	0,088 834	0,006 754
$f_{\mathrm{c,new}}$	Hz	0,346 425	0,348 765

B.3.8 Step 7: Final Bessel algorithm

As soon as the iteration criteria have been met, the final Bessel filter constants and the final Bessel algorithm are calculated in accordance with Step 2. In this example, the iteration criterion has been met after the second iteration (Δ = 0,006 754 < 0,01). The final algorithm is then used for determining the averaged smoke values (see B.4).

$$Y_i = Y_{i-1} + E \times \left(S_i + 2 \times S_{i-1} + S_{i-2} - 4 \times Y_{i-2}\right) + K \times \left(Y_{i-1} - Y_{i-2}\right) \tag{B.27}$$

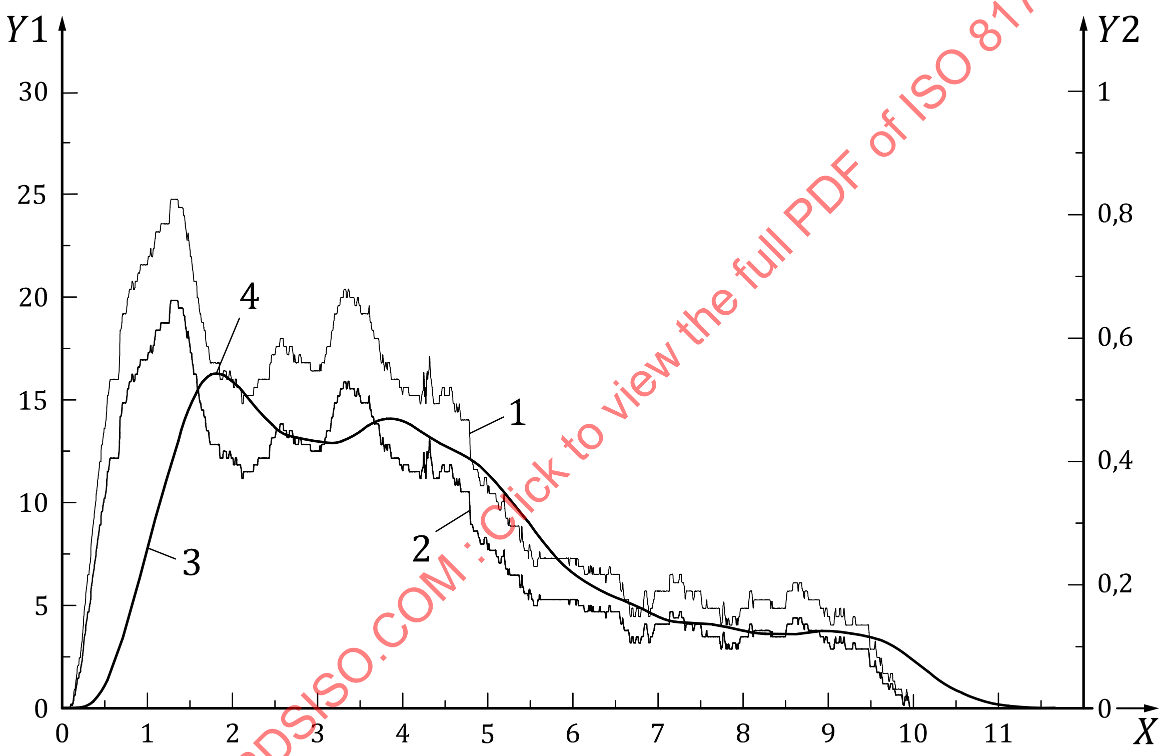
$$Y_i = Y_{i-1} + 8{,}383\,292 \times 10^{-5} \times \left(S_i + 2 \times S_{i-1} + S_{i-2} - 4 \times Y_{i-2}\right) + 0{,}968\,199 \times \left(Y_{i-1} - Y_{i-2}\right) \tag{B.28}$$

B.4 Calculation of the smoke values

B.4.1 General

In the following example, the general procedure of determining the final smoke value is given for PSV in accordance with 9.2.3. In this case, the Bessel filter designated in B.3 is used, and is applied to the light absorption coefficient, *k*, converted from the raw opacity signal according to Formula (6) of 9.1.2. If opacity is used for reporting the test results, the same filter algorithm is directly applied to the raw opacity signal. The procedure for LSV is identical.

Figure B.3 shows the traces of the measured raw opacity signal and of the unfiltered and filtered light absorption coefficients, *k*, of an acceleration. The maximum value $Y_{i,\max}$ (peak) of the filtered *k* trace is also indicated. Correspondingly, Tables B.3 and B.4 list the numerical values of index *i*, time (sampling rate of 150 Hz), raw opacity, unfiltered *k* and filtered *k*. Filtering was conducted using the constants of the Bessel algorithm designated in B.3. Due to the large amount of data, only those sections of the smoke trace around the beginning and the peak are tabled.



Key

*Y*1	opacity, *N*, expressed in per cent (%)	1	raw opacity
*Y*2	light absorption coefficient, *k*, expressed in reciprocal meters (m^{-1})	2	unfiltered absorption coefficient
X	time, expressed in seconds (s)	3	filtered absorption coefficient
		4	peak value of the filtered absorption coefficient

Figure B.3 — Traces of measured opacity *N* and unfiltered/filtered absorption coefficient *k*

Table B.3 — Values of opacity, *N*, and of unfiltered and filtered *k* at beginning of load step

Index *i*	Time s	Opacity *N* %	Unfiltered ***k*-value** m^{-1}	Unfiltered ***k*-value** m^{-1}
−2	0,000 000	0,000 000	0,000 000	0,000 000

Table B.3 *(continued)*

Index *i*	**Time** s	**Opacity** *N* %	**Unfiltered** ***k*-value** m^{-1}	**Unfiltered** ***k*-value** m^{-1}
−1	0,000 000	0,000 000	0,000 000	0,000 000
0	0,000 000	0,000 000	0,000 000	0,000 000
1	0,006 667	0,020 000	0,000 465	0,000 000
2	0,013 333	0,020 000	0,000 465	0,000 000
3	0,020 000	0,020 000	0,000 465	0,000 000
4	0,026 667	0,020 000	0,000 465	0,000 001
5	0,033 333	0,020 000	0,000 465	0,000 002
6	0,040 000	0,020 000	0,000 465	0,000 002
7	0,046 667	0,020 000	0,000 465	0,000 003
8	0,053 333	0,020 000	0,000 465	0,000 004
9	0,060 000	0,020 000	0,000 465	0,000 005
10	0,066 667	0,020 000	0,000 465	0,000 006
11	0,073 333	0,020 000	0,000 465	0,000 008
12	0,080 000	0,020 000	0,000 465	0,000 009
13	0,086 667	0,020 000	0,000 465	0,000 011
14	0,093 333	0,020 000	0,000 465	0,000 013
15	0,100 000	0,192 000	0,004 469	0,000 015
16	0,106 667	0,212 000	0,004 935	0,000 018
17	0,113 333	0,212 000	0,004 935	0,000 023
18	0,120 000	0,212 000	0,004 935	0,000 029
19	0,126 667	0,343 000	0,007 990	0,000 037
20	0,133 333	0,566 000	0,013 200	0,000 047
21	0,140 000	0,889 000	0,020 767	0,000 062
22	0,146 667	0,929 000	0,021 706	0,000 083
23	0,153 333	0,929 000	0,021 706	0,000 110
24	0,160 000	1,263 000	0,029 559	0,000 144
25	0,166 667	1,455 000	0,034 086	0,000 187
26	0,173 333	1,697 000	0,039 804	0,000 240
27	0,180 000	2,030 000	0,047 695	0,000 305
28	0,186 667	2,081 000	0,048 906	0,000 383
29	0,193 333	2,081 000	0,048 906	0,000 475
30	0,200 000	2,424 000	0,057 067	0,000 580
31	0,206 667	2,475 000	0,058 282	0,000 701
32	0,213 333	2,475 000	0,058 282	0,000 837
33	0,220 000	2,808 000	0,066 237	0,000 989
34	0,226 667	3,010 000	0,071 075	0,001 158
35	0,233 333	3,253 000	0,076 909	0,001 345
36	0,240 000	3,606 000	0,085 410	0,001 551
37	0,246 667	3,960 000	0,093 966	0,001 780
38	0,253 333	4,455 000	0,105 983	0,002 032
39	0,260 000	4,818 000	0,114 836	0,002 311
40	0,266 667	5,020 000	0,119 776	0,002 618

Table B.4 — Values of opacity, *N*, and of unfiltered and filtered *k* around PSV

Index *i*	Time s	Opacity *N*	Unfiltered ***k*-value** m^{-1}	Filtered ***k*-value** m^{-1}
259	1,726 667	17,182 000	0,438 429	0,538 748
260	1,733 333	16,949 000	0,431 896	0,539 244
261	1,740 000	16,788 000	0,427 392	0,539 689
262	1,746 667	16,798 000	0,427 671	0,540 082
263	1,753 333	16,788 000	0,427 392	0,540 426
264	1,760 000	16,798 000	0,427 671	0,540 720
265	1,766 667	16,798 000	0,427 671	0,540 968
266	1,773 333	16,788 000	0,427 392	0,541 170
267	1,780 000	16,788 000	0,427 392	0,541 327
268	1,786 667	16,798 000	0,427 671	0,541 441
269	1,793 333	16,798 000	0,427 671	0,541 514
270	1,800 000	16,793 000	0,427 532	**0,541 545**[a]
271	1,806 667	16,788 000	0,427 392	0,541 538
272	1,813 333	16,783 000	0,427 252	0,541 493
273	1,820 000	16,780 000	0,427 168	0,541 411
274	1,826 667	16,798 000	0,427 671	0,541 293
275	1,833 333	16,778 000	0,427 112	0,541 140
276	1,840 000	16,808 000	0,427 951	0,540 954
277	1,846 667	16,768 000	0,426 833	0,540 737
278	1,853 333	16,010 000	0,405 750	0,540 486
279	1,860 000	16,010 000	0,405 750	0,540 199
280	1,866 667	16,000 000	0,405 473	0,539 877
281	1,873 333	16,010 000	0,405 750	0,539 519
282	1,880 000	16,000 000	0,405 473	0,539 128
283	1,886 667	16,010 000	0,405 750	0,538 704
284	1,893 333	16,394 000	0,416 406	0,538 251
285	1,900 000	16,394 000	0,416 406	0,537 769
286	1,906 667	16,404 000	0,416 685	0,537 262
287	1,913 333	16,394 000	0,416 406	0,536 731
288	1,920 000	16,394 000	0,416 406	0,536 176
289	1,926 667	16,384 000	0,416 128	0,535 598
290	1,933 333	16,010 000	0,405 750	0,534 997
291	1,940 000	16,010 000	0,405 750	0,534 373
292	1,946 667	16,000 000	0,405 473	0,533 726
293	1,953 333	16,010 000	0,405 750	0,533 055
294	1,960 000	16,212 000	0,411 349	0,532 364
295	1,966 667	16,394 000	0,416 406	0,531 654
296	1,973 333	16,394 000	0,416 406	0,530 927
297	1,980 000	16,192 000	0,410 794	0,530 184
298	1,986 667	16,000 000	0,405 473	0,529 424
299	1,993 333	16,000 000	0,405 473	0,528 648

[a] Boldface indicates peak value.

Table B.4 *(continued)*

Index *i*	Time s	Opacity *N*	Unfiltered *k*-value m^{-1}	Filtered *k*-value m^{-1}
300	2,000 000	16,000 000	0,405 473	0,527 854
[a] Boldface indicates peak value.				

B.4.2 Calculation of the unfiltered *k*-value (optional)

The calculation procedure starts with the conversion from the as-measured opacity values to light absorption coefficient values. As indicated above, this is only required if the final smoke values are to be reported in units of light absorption coefficient. In this example, the conversion is done for index 262 (opacity N = 16,798 %) and an optical path length, L_A, of 0,43 m.

$$k = -\frac{1}{L_A} \times \ln\left(1 - \frac{N_A}{100}\right) \tag{B.29}$$

$$k = -\frac{1}{0,43} \times \ln\left(1 - \frac{16,798}{100}\right) = 0,427\,671\ \mathrm{m}^{-1} \tag{B.30}$$

This value corresponds to S_{262} given in B.4.3.

B.4.3 Calculation of Bessel averaged smoke (filtered k-value)

For starting the Bessel algorithm, $S_{i\text{-}1}$, $S_{i\text{-}2}$, $Y_{i\text{-}1}$, and $Y_{i\text{-}2}$ are set to zero. After the start, all individual smoke values are calculated (filtered) in the same way as described for index *i* = 262 resulting in the listing of filtered *k*-values of Table B.4. The following data are an excerpt of Table B.4 for index 262:

$$S_{262} = 0,427\,671\ \mathrm{m}^{-1} \tag{B.31}$$

$$S_{261} = 0,427\,392\ \mathrm{m}^{-1} \tag{B.32}$$

$$S_{260} = 0,431\,896\ \mathrm{m}^{-1} \tag{B.33}$$

$$Y_{261} = 0,539\,689\ \mathrm{m}^{-1} \tag{B.34}$$

$$Y_{260} = 0,539\,244\ \mathrm{m}^{-1} \tag{B.35}$$

In Formula (11), the Bessel constants of B.3 are used. The actual unfiltered *k*-value corresponds to S_{262} (S_i) as calculated above. S_{261} ($S_{i\text{-}1}$) and S_{260} ($S_{i\text{-}2}$) are the two preceding unfiltered *k*-values, Y_{261} ($Y_{i\text{-}1}$) and Y_{260} ($Y_{i\text{-}2}$) are the two preceding filtered *k*-values.

$$Y_i = Y_{i-1} + E \times \left(S_i + 2 \times S_{i-1} + S_{i-2} - 4 \times Y_{i-2}\right) + K \times \left(Y_{i-1} - Y_{i-2}\right) \tag{B.36}$$

$$\begin{aligned} Y_{262} &= 0,539\,689 + 8,383\,292 \times 10^{-5} \times \left(0,427\,671 + 2 \times 0,427\,392 + 9,431\,896 - 4 \times 0,539\,244\right) \\ &+ 0,968\,199 \times \left(0,539\,689 - 0,539\,244\right) = 0,540\,082\ \mathrm{m}^{-1} \end{aligned} \tag{B.37}$$

The highest filtered *k*-value of the complete smoke trace corresponds to PSV (PSV_F or PSV_3 or PSV_6 or PSV_9 depending on acceleration). In this example, the maximum is 0,541 545 m^{-1} found at index 270.

LSV is calculated accordingly.

As indicated above, the Bessel algorithm can be directly applied to the opacity N without conversion to k-value, if the final values are to be reported in units of opacity. Another possibility is the re-conversion of the k-value, as calculated above, to opacity.

Annex C
(informative)

Remarks on test cycles

The test procedures of this document are specifically intended for measuring exhaust gas smoke emissions from compression ignition engines operating under transient and steady-state operating conditions. The described procedures are applicable to test bed measurement, including certification or type approval of the engine to a regulated limit value, and with limitations and/or broader tolerances for field measurement as well. Deviations between both applications – test bed measurements and field measurements – are addressed in this document and need to be incorporated to the specific measurement requirement.

The test cycles as in Annex D, Annex E, Annex F and Annex G are representative of those engines which are used in applications as described in the distinguished cycles of ISO 8178-4:

— Annex D as described in cycle C1;

— Annex E as described in cycles D2, G1 and G2;

— Annex F as described in cycles E1, E2, E3 and E5;

— Annex G as described in cycle F.

Annex H describes the test cycle for determining smoke emissions at steady speeds over the full-load curve.

Generally, the application of this document is limited to engines up to 1 500 kW rated power output. However, the test procedures of this document can likewise be used for measuring smoke emissions of engines with greater output but limitations in following a transient operation with increased engine size shall be acknowledged. This document does not stipulate requirements for an engine operation in conjunction with its smoke emission characteristic beyond an approval of the engine or equipment-manufacturer.

However, it is recognized that regulators may want a more discerning field measurement – one that can detect if a particular in-use engine is abnormal compared to smoke values obtained during certification/type-approval. Conceptually, this could be done by comparing the in-use smoke value at the in-use acceleration time to the certification/type-approval smoke value (actual or interpolated) at the same certification/type-approval acceleration time; e.g., if the certification/type approval FAT is 1,0 s, then smoke test the values determined at FAT plus 3 × FAT, 6 × FAT and 9 × FAT, or 1 s, 3 s, 6 s and 9 s. If the in-use acceleration time is 4 s, then one could determine an interpolated certification/type approval smoke value for 4 s by linearly interpolating between the 3 × FAT and 6 × FAT certification/type approval smoke values. However, in order to use the certification/type-approval smoke values in this manner, various sources of smoke data variability should be assessed.

There are two types of engine variability to consider; the variability between ratings and the variability between engines of the same rating. There are typically a number of engine ratings in a family or group and the smoke signature will vary somewhat from one rating to the next. The results of field measurements on one particular rating cannot be expected to correspond precisely to tests on another rating. Secondly, production tolerances lead to a different smoke level from one engine to the next, even for engines of the same rating. In order to use the results of this document in the in-use inspection program, a statistically valid sample of test bed measurement results should be obtained. One should determine the variability both between ratings in a family or group and among different engines of the same rating in order to judge if an in-use engine is “good” or “bad”. Failure to make such a determination could jeopardize the credibility of an in-use program. The program should be designed so as not to fail an engine that has a smoke level higher than the particular certification test engine but still within normal production tolerances.

Finally, measurement variability needs also to be considered. It should be noted that the field measurements in accordance with the provisions of this document are likely to be less precise than test bed measurements. Therefore, the limit values established for certification/type approval may be inappropriately low for an in-use program. Additional test data are needed to determine the appropriate offset, if any, between a test bed smoke limit and an in-use smoke limit.

It should be noted that an acceptable field smoke test may not be possible on certain machines, specifically those machines for which the free acceleration time of the engine in the machine is greater than 9 × FAT for the engine tested in accordance with this document.

There are a number of situations which could cause the in-use engine to fail the smoke test. The engine may be misapplied to the machine, with an undersized intake, exhaust or cooling system that fails to meet the engine manufacturer's specifications. Furthermore, infrequent or improper maintenance could also cause the engine to fail the smoke test. Additionally, the in-use fuel could cause the engine to have high smoke levels.

It is anticipated that measuring difficulties will be experienced on engines that have only a few (one, two and perhaps three) cylinders feeding into an exhaust pipe. These few-cylinder engines will have substantial variation in exhaust pressure and flow rate, leading to reduced accuracy and increased variability.

It is envisioned that ISO 8178-9 tests would be run on a "parent engine" of an engine family (ISO 8178-7) or an engine group (ISO 8178-8) on a test bed, and that the results of the tests would be compared to the regulated limit value. The most straightforward way to apply this document is as a check for "gross emitters" – those engines whose in-use smoke levels exceed the new-engine regulated limit value by a substantial amount.

Annex D
(normative)

Test cycle for variable-speed non-road engines

D.1 General

The smoke cycle described in this annex consists of two parts: a free acceleration test and a loaded acceleration test. This smoke cycle is applicable to those variable speed engines that are included in the test cycle type C1 of ISO 8178-4. The transient smoke cycle is expected to complement the steady-state emission measurements and the two together provide for control of emissions under a wide variety of operating conditions. Furthermore, the smoke test is intended to offer a method of characterizing engine emissions when installed in a machine. Moreover, it provides a measure of smoke emissions at the manufacturer and in-field.

The test cycle type C1 of ISO 8178-4 is for "Compression-ignition engine powered non-road machinery and industrial equipment". Typical examples of applications included in the scope of this annex are:

— industrial drilling rigs, compressors etc.,

— construction equipment including wheel loaders, bulldozers, crawler tractors, crawler loaders,

— truck-type loaders, off-highway trucks, hydraulic excavators etc.,

— agricultural equipment, rotary tillers,

— forestry equipment,

— self-propelled agricultural vehicles (including tractors),

— material handling equipment,

— fork lift trucks,

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

— snow plough equipment,

— snow tractors, airport support equipment,

— aerial lifts, and

— mobile cranes.

This list is not exhaustive.

NOTE 1 Compression-ignition engines with rated power typically below 19 kW intended for applications listed under test cycles type G, can be tested according to the test cycles type 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.

The transient smoke test described in this annex contains acceleration rates that may not be achievable by all sizes of engines or may not be relevant to certain applications. The scope of this annex has thus far been confirmed for engines with a rated power output up to 1 500 kW. For engines with higher power output, this annex may also be applied if the involved parties agree.

Engines with only one or two cylinders may have special difficulty in running the cycles. Additionally, smoke measurement from one- or two-cylinder engines may include a pulsation that precludes reliable measurements unless a damping volume (muffler) is used. Special test procedures for unique applications may be used if agreed upon by the parties involved.

D.2 Test cycle

D.2.1 General

Acceleration times between the free acceleration time and nine times the free acceleration time are employed in this test procedure. This will allow the smoke tests to bracket the free acceleration rates typical of those which occur when the engine undergoes a free acceleration in the machine and will also include loaded acceleration rates representative of those which occur during machine operation. The use of a number of acceleration times will provide smoke values under a variety of operating conditions, which will facilitate the use of the family or group testing concept contained in ISO 8178-7 and ISO 8178-8. Different acceleration times may be more relevant for certain engines and applications and may be used if agreed upon by the parties involved.

D.2.2 Preconditioning of the engine

The engine shall be warmed up at the rated power in order to stabilize the engine parameters in accordance with the recommendations of the manufacturer.

A preconditioning phase should also protect the actual measurement against the influence of deposits in the exhaust system resulting from a former test.

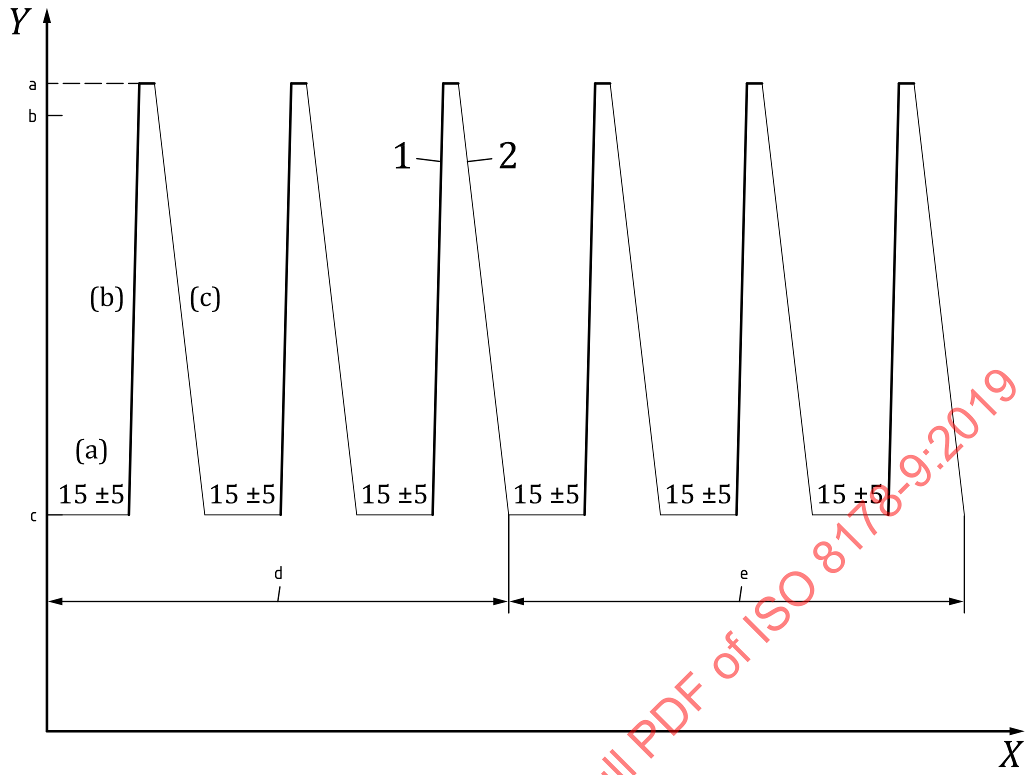
D.2.3 Free acceleration test

D.2.3.1 General

The free acceleration test is the first part of the test cycle for engine applications covered by this annex. It shall be performed immediately following the preconditioning, as described in D.2.2. The free acceleration test is a procedure that accelerates the engine from low idle speed to high idle speed against its own internal inertia and the inertia provided by the engine's flywheel. The engine tested shall be equipped with a flywheel and other rotating components that provide an inertia on the low end of the range of inertias available for the rating that is being tested. This will provide a value for FAT that is typically of the fastest acceleration that occurs in practice, thus providing for smoke control under the widest range of conditions. The free acceleration test is intended to be run with the engine decoupled from the dynamometer. For in-field testing, where decoupling is not possible, parasitic and external loads shall be minimized. The involved parties shall agree on the setup prior to testing.

It is permissible to use a clutch to decouple the engine from the dynamometer as long as the inertia of that portion of the clutch that continues to rotate with the engine does not exceed 25 % of the total engine inertia. It is permissible to leave the engine coupled to the dynamometer if the dynamometer is used to simulate zero inertia. The free acceleration test can be run with the dynamometer connected if agreed upon by the parties involved.

The free acceleration test has the following general sequence. The sequence is shown graphically in Figure D.1.



Key

X time, expressed in seconds (s)

Y engine speed

1 full throttle

2 closed throttle

a High idle speed.

b Rated speed.

c Idle speed.

d Practice runs.

e Actual runs.

NOTE (a), (b) and (c) refer to D.2.3.1 a), b), and c).

Figure D.1 — Free acceleration test

a) The engine shall be stabilized at the low idle speed for 15 s ± 5 s.

b) The speed control lever shall be moved rapidly to and held in the wide-open position until the engine reaches its governed high idle (no load) speed.

c) The speed control lever shall be returned to the closed position and the engine allowed to return to its low idle speed.

d) The above sequence shall be repeated 2 times as practice runs in order to clean out the exhaust system.

e) After the 3 practice runs, the above sequence shall be repeated until 3 successive runs meet the stability criteria as described in D.2.3.2.

D.2.3.2 Test validation criteria — Free acceleration test

The free acceleration test results shall be considered valid only after the following test cycle criteria have been met.

The arithmetical difference between the highest and lowest maximum 1 s Bessel averaged smoke values from the three successive free accelerations shall not exceed 5 % opacity.

Additional test validation criteria are given in Clause 5 and 7.3.3.2.

D.2.3.3 Determination of free acceleration time (FAT)

FAT is the basis for loaded acceleration times (D.2.5.2). The free acceleration time for an individual free acceleration in D.2.3.1 e) is the time the engine speed goes from 5 % above low idle speed to 95 % of rated speed. FAT is the average of the three individual free accelerations in D.2.3.1 e).

D.2.4 Reconditioning of the engine

The engine shall be reconnected to the dynamometer if it has been disconnected. The engine shall be warmed up at the rated power in order to stabilize the engine parameters according to the recommendations of the manufacturer.

A reconditioning phase should also protect the actual measurement against the influence of deposits in the exhaust system resulting from a former test.

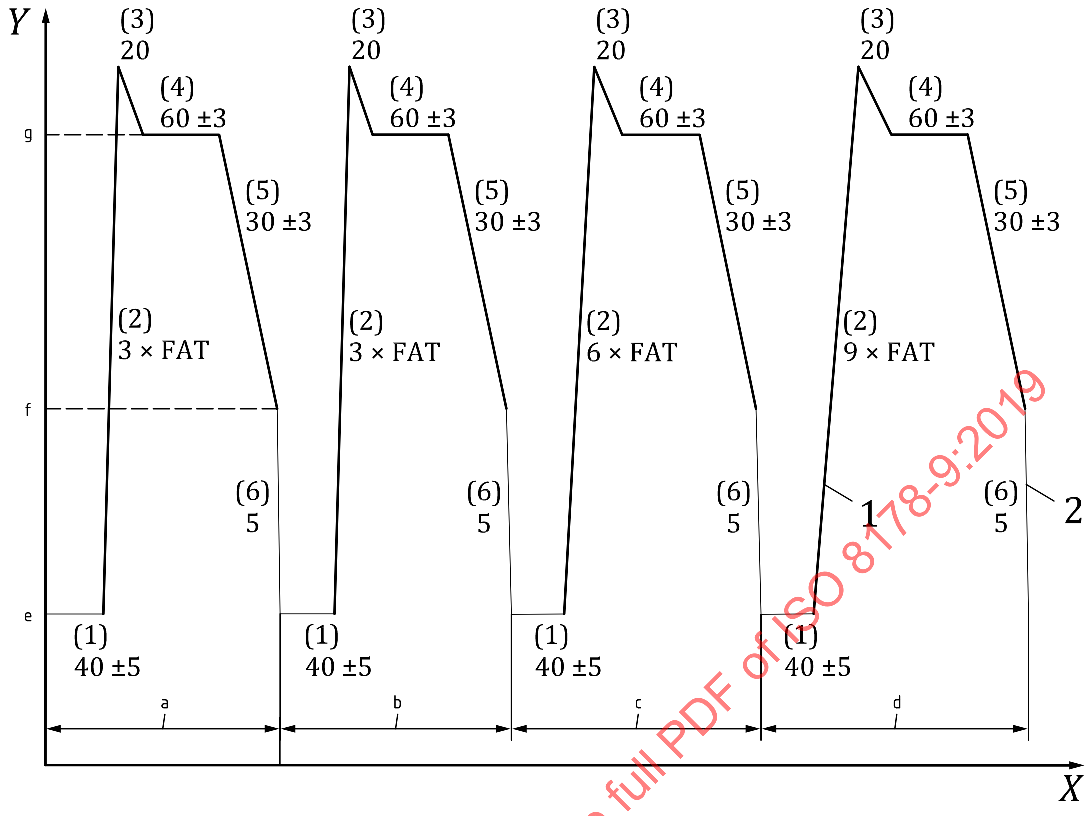
D.2.5 Loaded transient test

D.2.5.1 General

The loaded transient test is the second part of the test cycle, and has the sequence as described in D.2.5.3. It shall immediately follow the reconditioning of the engine. The sequence is shown graphically in Figure D.2. For this test, a defined load has to be applied which requires a dynamometer.

D.2.5.2 Loaded transient test times

The acceleration times of the loaded transient test are multiples of the free acceleration test time determined in D.2.3.3. The engine acceleration times to be used in the loaded transient test are to be 3 × FAT, 6 × FAT and 9 × FAT. Each of these resultant times is to be the time from when the engine speed is 5 % above low idle speed until it reaches 95 % of rated speed. The values of 3 × FAT, 6 × FAT and 9 × FAT may be rounded to the nearest second.



Key

X	time, expressed in seconds (s)
Y	engine speed
1	full throttle
2	closed throttle
a	Loaded acceleration I (conditioning).
b	Loaded acceleration II (3 × FAT).
c	Loaded acceleration III (6 × FAT).
d	Loaded acceleration IV (9 × FAT).
e	Idle speed.
f	Intermediate speed.
g	Rated speed.

NOTE (1), (2), (3), (4), (5) and (6) refer to D.2.5.3 a).

Figure D.2 — loaded acceleration test

D.2.5.3 Conducting a loaded transient test

The loaded transient test begins with a conditioning cycle in order to improve the repeatability of the results. The conditioning cycle is followed by three loaded acceleration cycles that differ only in the rate of the loaded acceleration. The loaded acceleration is followed by full load rated speed stabilization and engine lug down. The linearity specifications in 2) below apply only to electric dynamometers and are intended to prevent the engine from being operated in an unusual fashion so as to achieve low smoke values. Furthermore, no motoring of the engine is allowed. The loaded transient test sequence is as follows:

a) Conditioning cycle:

   1) The engine shall be operated with the speed control lever in the closed position at low idle speed for 40 s ± 5 s.

   2) From the low idle speed the speed control lever shall be moved rapidly to, and held in, the wide open position. The engine shall accelerate such that the time from 5 % above low idle speed to 95 % of the rated speed is 3 × FAT seconds. The engine speed versus time between 5 % above low idle speed and 95 % of rated speed shall be linear within ±100 min^{-1} or ±5 % of rated speed, whichever is greater.

   3) Within 20 s of the engine reaching 95 % of rated speed point, the necessary dynamometer load shall be applied in order to stabilize the engine at rated speed, full load.

   4) Rated speed and full load shall be maintained for 60 s ± 3 s.

   5) The dynamometer shall be adjusted as necessary to lug the speed down under full load conditions to the intermediate speed. The rate of speed change shall be linear, and the time from the start of the lug down until reaching the intermediate speed point shall be 30 s ± 3 s.

   6) Within 5 s of the engine reaching the intermediate speed, the speed control level shall be returned to the closed position and the engine allowed to return to its low idle speed.

b) 3 × FAT loaded acceleration:

   Repeat 1) to 6).

c) 6 × FAT loaded acceleration:

   Repeat 1) to 6) with the loaded acceleration time in 2) replaced with 6 × FAT seconds.

d) 9 × FAT loaded acceleration:

   Repeat 1) to 6) with the loaded acceleration time in 2) replaced with 9 × FAT seconds.

The above steps shall be repeated until the engine speed, time and linearity criteria of this clause have been satisfied except if the acceleration is below 0,5 s.

D.2.5.4 Conducting a loaded transient test — Alternative procedure

As an alternative to the single "four-cycle" test described in D.2.5.3, the loaded transient test can be conducted by running three "two-cycle" tests. This will allow inertia to be changed between tests, so that the tests can be run without using a computer-controlled dynamometer. Each test will consist of the conditioning cycle 1) to 6) of D.2.5.3 a) being run two times. For the first test, the loaded acceleration time for D.2.5.3 a) 2) will be 3 × FAT. For the second test, the time for D.2.5.3 a) 2) will be 6 × FAT. For the third test, the time for D.2.5.3 a) 2) will be 9 × FAT. Results from the second cycle of each test shall be used for official results.

D.3 Analysis of results

D.3.1 General

This clause describes how to analyse the results of the free acceleration test and the loaded transient test. Many opacimeters used for this test have a smoke output signal that is an $X = 0,5$ s Bessel average smoke according to the algorithm described in 9.2. For these opacimeters, further signal conditioning to produce the "$X = 1$ s" smoke results is needed, and the value of $(t_p^2 + t_e^2)$ used in Formula (7) is 0,25. Analysis of raw smoke results, those not already processed according to the 0,5 s Bessel algorithm, should use a $(t_p^2 + t_e^2)$ value that represents the opacimeter system.

D.3.2 Peak smoke value (PSV_F, PSV_3, PSV_6, PSV_9)

Values for PSV shall be calculated for the free acceleration test (PSV_F) and each of the three loaded accelerations (PSV_3, PSV_6 and PSV_9). PSV_F is the average of the highest 1 s Bessel averaged smoke values from the three successive free acceleration events. PSV_3, PSV_6 and PSV_9 are the highest values of the X = 1 s Bessel average smoke that occur during the corresponding accelerations of the loaded transient test. Care shall be taken to ensure that the smoke data that is analysed corresponds to the time during which the acceleration event occurs. The free acceleration event is D.2.3.1 b). Loaded accelerations of time 3 s, 6 s and 9 s are b) 2), c) and d) respectively of D.2.5.3 (or their equivalents in D.2.5.4).

The methodology for calculating Bessel averaged numbers can be found in 9.2. For peak smoke values, the value of X in Formula (7) is 1 s.

D.3.3 Lug smoke value (LSV)

Values for LSV shall be calculated for each lug mode that occurs during the loaded transient tests (LSV_3, LSV_6 and LSV_9). These values are the highest 1 s Bessel averaged values obtained during the three corresponding lug modes of the loaded transient test.

NOTE The three lug modes (at the end of the 3 × FAT, 6 × FAT, and 9 × FAT accelerations) are identical, and thus are expected to yield similar results.

Care shall be taken to ensure that the smoke data that is analysed corresponds to the time during which the lugging event occurs. The lugging event is b) 5), c) and d) respectively of D.2.5.3 (or their equivalents in D.2.5.4).

The methodology for calculating Bessel averaged numbers can be found in 9.2. For lug smoke values, the value of X in Formula (7) is 1 s.

The lug smoke value that is reported, LSV, is the average of LSV_3, LSV_6 and LSV_9.

D.4 Reported results

In accordance with Annex I, the following smoke values shall be reported: PSV_F, PSV_3, PSV_6, PSV_9 and LSV.

Annex E
(normative)

Test cycle for constant-speed non-road engines

E.1 General

Engines within the scope of this annex either cannot or do not operate at varying speeds. However, some constant speed engines can undergo rapid and substantial changes in load, an event that can lead to brief episodes of smoke emittance.

The transient smoke cycle is expected to complement the steady-state emission measurements and the two together will provide for control of emissions under a wide variety of operating conditions. Furthermore, the smoke test is intended to offer a method of characterizing an engine's emissions when installed in a machine and to provide for measurement of smoke emissions both at the manufacturer and in the field.

Testing of the engine with the highest fuel flow (the parent engine in the family according to the provisions of ISO 8178-7) is expected to yield the worst case of smoke emission.

This annex is applicable to the test cycles type D2, G1, and G2 as defined in ISO 8178-4 and has thus been confirmed for engines with a rated power output up to 1 500 kW. For engines with higher power output, this annex may also be applied if the involved parties agree.

Typical applications include, but are not limited to:

a) Test cycle type 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.

b) Test cycle type 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.

c) Test cycle type G2:

— portable generators, pumps, welding sets and air compressors;

— lawn and garden equipment which operates at engine-rated speed.

E.2 Test cycle

E.2.1 Engine load step

This subclause describes how to calculate the load step applied to the engine. The load step that shall be applied is a function of the brake mean effective pressure (p_{me}) at the declared power. When the constant speed engine is used in a generator application, the declared power shall be the power produced by the engine at the prime power rating of the generator, as defined in ISO 8528-1. For engines used in applications other than generators, the declared power shall be the rated power of the engine as specified by the manufacturer.

The engine's p_{me} shall be calculated as follows:

$$p_{me} = \frac{P \times 2\,000}{V_d \times n} \qquad \text{for four-stroke engines}$$

$$p_{me} = \frac{P \times 1\,000}{V_d \times n} \qquad \text{for two-stroke engines}$$

where

p_{me} is the brake mean effective pressure, expressed in kilopascals (kPa);

P is the declared power, expressed in kilowatts (kW);

V_d is the displaced volume of the engine, expressed in litres (l);

n is the engine speed, expressed in reciprocal seconds (s^{-1}).

Figures E.1 and E.2 specify the amount of load (percent of declared power) that shall be applied to the engine, as a function of the p_{me} of the engine. Recognizing that most constant speed applications are in generators, the load step is that specified for generators in ISO 8528-5. Figure E.1 applies to four-stroke engines and Figure E.2 applies to two-stroke engines. The load given by Figure E.1 or E.2 is that load which is applied in E.2.3 c).

E.2.2 Preconditioning of the engine

The engine shall be warmed up at the rated power in order to stabilize the engine parameters according to the recommendations of the manufacturer.

A preconditioning phase should also protect the actual measurement against the influence of deposits in the exhaust system resulting from a former test.

E.2.3 Test procedure

a) Immediately after preconditioning operate the engine for 40 s ± 5 s at fuel stop power and record its smoke emission.

b) Operate the engine at 10 % of declared power for 40 s ± 5 s.

c) Apply the step load specified in E.2.1 as rapidly as possible.

NOTE The time it takes the engine to accept the step load will vary depending upon the requirements of the application.

d) Operate the engine at this load for 40 s ± 5 s.

e) Repeat steps b) to d) to complete three cycles.

E.2.4 Test Validation Criteria

The test results shall be considered valid only after the following test cycle criteria have been met. The arithmetical difference between the highest and lowest maximum 1 s Bessel averaged smoke values from the three successive steps shall not exceed 5 % opacity.

Additional test validation criteria are given in Clause 5 and 7.3.3.2.

E.3 Analysis of results

E.3.1 General

This clause describes how to analyse the results of the smoke test.

Many opacimeters used for this test have a smoke output signal that is an X = 0,5 s Bessel average smoke according to the algorithm described in 9.2. For these opacimeters further signal conditioning to produce the “X = 1 s” smoke results is needed, and the value of $(t_p^2 + t_e^2)$ used in Formula (7) is 0,25.

Analysis of raw smoke results, those not already processed according to the 0,5 s Bessel algorithm, should use a $(t_p^2 + t_e^2)$ value that represents the opacimeter system.

E.3.2 Steady-state smoke value (SSSV)

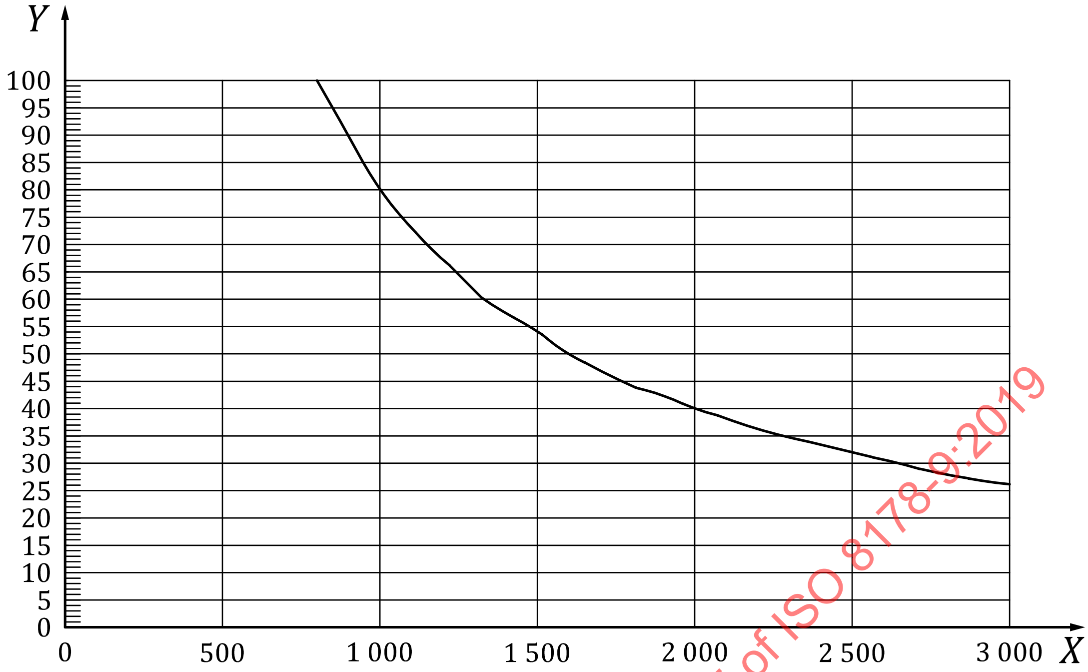
SSSV is the highest smoke value recorded during E.2.3 a). No Bessel averaging is required of a steady-state smoke value.

E.3.3 Peak smoke value (PSV)

Determine the highest 1 s Bessel average smoke values (PSV_1, PSV_2, PSV_3) that occur during the three replicates of E.2.3 c). Care shall be taken to ensure that the smoke data that is analysed corresponds to the time during which the load application event occurs. PSV_a is the average of the three highest 1 s Bessel averaged smoke values obtained during the load application tests.

E.4 Reported results

In accordance with Annex I, the following smoke values shall be reported: PSV_a and SSSV.

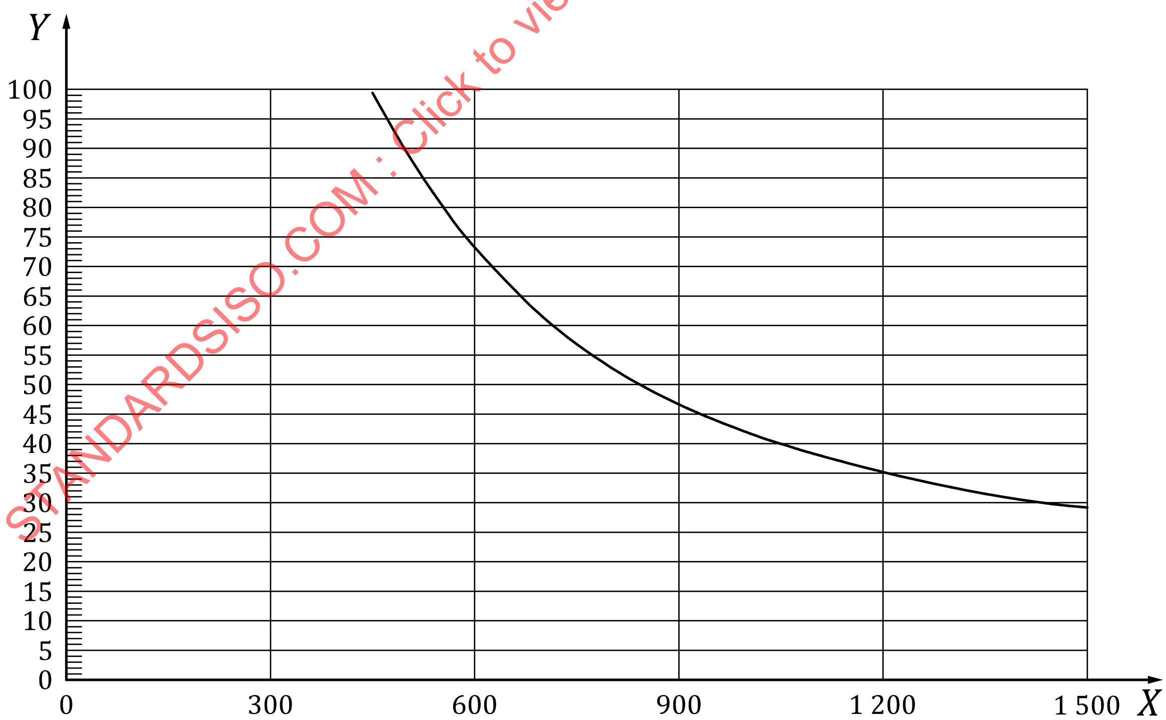


Key

Y % of declared power

X brake mean effective pressure (p_{me}) of declared power, expressed in kilopascals (kPa)

Figure E.1 — Load step for four-stroke engines



Key

Y % of declared power

X brake mean effective pressure (p_{me}) of declared power, expressed in kilopascals (kPa)

Figure E.2 — Load step for two-stroke engines

Annex F
(normative)

Test cycle for marine propulsion engines

F.1 General

Marine engine operations occurs over a much more limited combination of speed and torque as compared to on-road and mobile non-road engines. This is partly due to the fact that marine engines are not equipped with a shiftable gearbox and partly due to the physical behaviour of the power transmission from the propeller to the water.

There are two principle torque-to-speed relationships: the propeller law, defined by torque = $f(n^2)$, where n is the number of revolutions of the crankshaft in a given period of time, with a fixed propeller or water jet, and the constant-speed law (comparable to generator applications), which is applicable with a controllable-pitch propeller. These principles correspond with the test cycles type E1, E2, E3 and E5 of ISO 8178-4. Therefore, the smoke during the engine load increase, for both cases (with or without speed increase), is more stable and influenced mainly by the rate of load increase. This rate is subjected to automatic limitation procedures of various kinds.

One example is the power-increase rate. For marine engines, the power-increase rate is slower as compared to on-road or mobile non-road engines. This is partly due to the physical behaviour of the power transmission from the propeller to the water. In all such cases, the engine will be controlled by its management or control system depending on the kind of the vessel. This “standard case” is also the worst case and is very suitable as the basis for dynamic smoke measurements. Engines with various management or control settings can be combined in engine families or groups, with a worst case being tested for the complete family or group.

On board vessels, safety is always of paramount importance. Therefore, although automatic control is the general rule, an exception shall remain for emergency cases where overriding of the system is needed to reduce imminent danger. In such an emergency case, there might be an increased smoke rate due to greater engine acceleration. Such increased smoke rates are not considered in this annex.

For testing of variable-speed, variable-load auxiliary marine engines see Annex D. For testing of constant-speed auxiliary marine engines see Annex E.

F.2 Application of the smoke-test cycle

The smoke-test cycle described in this annex is applicable to those engines which are included in the tests cycles type E1, E2, E3 and E5 cycles of ISO 8178-4. The factor governing whether to use the test cycle in this annex is the loaded acceleration time. This should be 20 s ± 5 s or be as declared by the manufacturer, taking into account the engine management or control system. Those marine propulsion engines that can be used in the application for mobile non-road engines may optionally be tested according the procedures in Annex D.

The following are typical applications:

— Test cycle type E1: compression ignition engines for propulsion of craft less than 24 m in length except tug boats and push boats;

— Test cycle type E2: constant-speed heavy duty engines for propulsion of ships of any length including diesel-electric drive and variable-pitch propeller applications;

— Test cycle type E3: propeller-law heavy-duty engines for propulsion of ships of any length;

— Test cycle type 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).

This annex has been confirmed for engines with rated power of up to 1 500 kW. For engines with higher power output, this annex may also be applied if the involved parties agree.

F.3 Test cycle

F.3.1 General

During smoke measurement in the test under transient load (described in detail in F.3.2 and F.3.3), the engine load is increased as rapidly as possible, either on the propeller curve or at constant speed. The load-increase rate, and thus the load-increase time, is controlled by the engine management or control system.

This cycle is suitable for use on the test stand as well as for measurements with the engine installed in the vessel.

When engine smoke is measured on the test stand, the load-increase time can be varied within a range that covers the service conditions of an engine family or engine group, which shall be defined in accordance with ISO 8178-7 and ISO 8178-8.

F.3.2 Preconditioning of the engine

The engine shall be warmed up at rated power in accordance with the manufacturer's recommendations in order to stabilize the engine operating parameters.

NOTE This preconditioning phase also insulates the current measurement against the influence of a previous test and is considered as creating reference conditions.

F.3.3 Conducting a test under transient load

F.3.3.1 General

The test under transient load shall be performed immediately following the preconditioning, as described in F.3.2. Conducting a test under transient load begins with a conditioning cycle to improve the repeatability of the results. The conditioning cycle is followed by three load-increase cycles. The loaded transient test sequence is described in F.3.3.4 and F.3.3.5.

F.3.3.2 Variable-speed engines

The test under transient load consists of accelerating the engine from low idle speed to 80 % of rated speed against the load that is described by the function torque = $f(n^2)$. The sequence is shown graphically in Figure F.1. During acceleration, the engine load is controlled so the engine torque corresponds to the transient load curve. For variable-speed engines the transient load curve is typically a propeller curve, defined by $f(n^3)$, at the end point of which the rated power is reached at the rated speed.

NOTE The variable *n* is the number of revolutions of the crankshaft in a given period of time.