



BSI Standards Publication

Reciprocating internal combustion engines — Exhaust emission measurement

Part 9: Test cycles and test procedures
for test bed measurement of exhaust
gas smoke emissions from compression
ignition engines operating under
transient conditions

National foreword

This British Standard is the UK implementation of ISO 8178-9:2012. It supersedes BS ISO 8178-9:2000, which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee MCE/14/-/3, RIC engines - Emissions.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

© The British Standards Institution 2012
Published by BSI Standards Limited 2012

ISBN 978 0 580 70772 8

ICS 13.040.50; 27.020

Compliance with a British Standard cannot confer immunity from legal obligations.

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 August 2012.

Amendments issued since publication

Date	Text affected
------	---------------

**Reciprocating internal combustion
engines — Exhaust emission
measurement —**

Part 9:

**Test cycles and test procedures for
test bed measurement of exhaust gas
smoke emissions from compression
ignition engines operating under
transient conditions**

*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*





COPYRIGHT PROTECTED DOCUMENT

© ISO 2012

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either ISO at the address below or ISO's member body in the country of the requester.

ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

Published in Switzerland

Contents

Page

Foreword	iv
Introduction	v
1 Scope	1
2 Normative references	1
3 Terms and definitions	2
4 Symbols and units	4
5 Test conditions	5
5.1 Ambient test conditions	5
5.2 Power	5
5.3 Engine air inlet system	6
5.4 Engine exhaust system	6
5.5 Cooling system	6
5.6 Lubricating oil	6
5.7 Engines with charge air cooling	6
5.8 Test fuel temperature	6
6 Test fuels	6
7 Measurement equipment and accuracy	7
7.1 General	7
7.2 Dynamometer specification	7
7.3 Determination of smoke	7
7.4 Accuracy	9
8 Calibration of the opacimeter	9
8.1 General	9
8.2 Calibration procedure	9
9 Test run	9
9.1 Installation of the measuring equipment	9
9.2 Checking of the opacimeter	10
9.3 Test cycle	10
9.4 Determination of effective optical path length (L_A)	10
10 Data evaluation and calculation	10
10.1 Data evaluation	10
10.2 Bessel algorithm	12
10.3 Ambient correction	13
10.4 Test report	14
11 Determination of smoke	14
11.1 General	14
11.2 Full-flow opacimeter	15
11.3 Partial-flow-opacimeter	16
Annex A (normative) Test cycle for variable-speed off-road engines	19
Annex B (normative) Test cycle for constant-speed off-road engines	26
Annex C (informative) Remarks on test cycles	30
Annex D (informative) Example of calculation procedure	31
Annex E (normative) Test cycle for marine propulsion engines	42
Annex F (normative) Test cycle for variable speed engines type F (rail traction)	48
Bibliography	52

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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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.

ISO 8178-9 was prepared by Technical Committee ISO/TC 70, *Internal combustion engines*, Subcommittee SC 8, *Exhaust gas emission measurement*.

This second edition cancels and replaces the first edition (ISO 8178-9:2000, ISO 8178-9:2000/AMD 1:2004), which has been technically revised.

ISO 8178 consists of the following parts, under the general title *Reciprocating internal combustion engines — Exhaust emission measurement*:

- *Part 1: Test-bed measurement of gaseous and particulate exhaust emissions*
- *Part 2: Measurement of gaseous and particulate exhaust emissions under field conditions*
- *Part 3: Definitions and methods of measurement of exhaust gas smoke under steady-state conditions*
- *Part 4: Steady-state test cycles for different engine applications*
- *Part 5: Test fuels*
- *Part 6: Report of measuring results and test*
- *Part 7: Engine family determination*
- *Part 8: Engine group determination*
- *Part 9: Test cycles and test procedures for test bed measurement of exhaust gas smoke emissions from compression ignition engines operating under transient conditions*
- *Part 10: Test cycles and test procedures for field measurement of exhaust gas smoke emissions from compression ignition engines operating under transient conditions*
- *Part 11: Test-bed measurement of gaseous and particulate exhaust emissions from engines used in nonroad mobile machinery under transient test conditions*

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 programmes. Different smoke measurement procedures exist to meet the needs of various regulatory agencies and industries. The two methods typically used are the filter smoke meter method and the opacimeter.

The purpose of ISO 8178 is to combine the key features of several existing smoke measurement procedures as much as technically possible. ISO 8178-4 specifies a number of different test cycles to be used to characterize gaseous and particulate emissions from nonroad engines. 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. Within ISO 8178-4 it was possible to characterize and control gaseous and particulate emissions from nonroad engines using a variety of steady-state operating points. To properly characterize and control smoke emissions from many engine applications a transient smoke test cycle is needed.

This part of ISO 8178 is intended for the measurement of the emissions of smoke from compression ignition internal combustion engines. It applies to engines operating under transient conditions, where the engine speed or load, or both, changes with time; note that the smoke emissions from typical well-maintained naturally-aspirated engines under transient conditions will generally be the same as the smoke emissions under steady-state conditions.

Only opacimeter-type smoke meters are intended to be used for making the smoke measurements described in this part of ISO 8178, which allows the use of either full-flow or partial-flow opacimeters and corrects accounts for differences in response time between the two types of opacimeters, but does not account for any differences due to differences in temperatures at the sampling zone.

The test cycle described in Annex E is representative for those engines that are used in applications as described in the E1, E2, E3 and E5 cycles of ISO 8178-4:2007.

The test cycle described in Annex F is representative for those engines that are used in applications as described in the F cycle of ISO 8178-4:2007.

Reciprocating internal combustion engines — Exhaust emission measurement —

Part 9:

Test cycles and test procedures for test bed measurement of exhaust gas smoke emissions from compression ignition engines operating under transient conditions

1 Scope

This part of ISO 8178 specifies the measurement procedures and test cycles for the evaluation of smoke emissions from compression ignition engines on the test bed.

For transient smoke test cycles, smoke testing is conducted using smokemeters which operate on the light extinction principle. The purpose of this part of ISO 8178 is to define the smoke test cycles and the methods used to measure and analyse smoke. Specifications for measurement of smoke using the light extinction principle can be found in ISO 11614. The test procedures and measurement techniques described in Clauses 1 to 11 of this part of ISO 8178 are applicable to reciprocating internal combustion (RIC) engines in general. However, an engine application can only be evaluated using this part of ISO 8178 once the appropriate test cycle has been developed. Annexes A, B, E and F to this part of ISO 8178 each contain a test cycle that is relevant only for those specific applications listed in the Scope 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, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 8178-4:2007, *Reciprocating internal combustion engines — Exhaust emission measurement — Part 4: Steady-state test cycles for different engine applications*

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

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

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

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.

3.1

exhaust gas smoke

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

NOTE Black smoke (soot) is mainly comprised of carbon particles; blue smoke is usually due to droplets resulting from the incomplete combustion of fuel or lubricating oil; white smoke is usually due to condensed water and/or liquid fuel; yellow smoke is caused by NO_2 .

3.2

transmittance

τ

fraction of light, expressed as a percentage, transmitted from a source through a smoke-obscured path and which reaches the observer or the instrument receiver

3.3

opacity

N

fraction of light, expressed as a percentage, transmitted from a source through a smoke-obscured path and which is prevented from reaching the observer or the instrument receiver

NOTE $N = 100 - \tau$

3.4

optical path length

3.4.1

effective optical path length

L_A

length of the smoke-obscured optical path between the opacimeter light source and the receiver, expressed in metres and corrected, as necessary, for non-uniformity due to density gradients and fringe effect

NOTE Portions of the total light source to receiver path length which are not smoke obscured do not contribute to the effective optical path length.

3.4.2

standard effective optical path length

L_{AS}

measurement used to ensure meaningful comparisons of quoted opacity values

NOTE L_{AS} values are defined in 10.1.4.

3.5

light absorption coefficient

k

fundamental means of quantifying the ability of a smoke plume or smoke-containing gas sample to obscure light

NOTE By convention, the light absorption coefficient is expressed in reciprocal metres (m^{-1}). The light absorption coefficient is a function of the number of smoke particles per unit gas volume, the size distribution of the smoke particles and the light absorption and scattering properties of the particles. In the absence of blue, white or yellow smoke or ash, the size distribution and the light absorption/scattering properties are similar for all diesel exhaust gas samples and the light absorption coefficient is primarily a function of the smoke particle density.

3.6

Beer-Lambert law

mathematical equation describing the physical relationships between the light absorption coefficient (k), the smoke parameters of transmittance (τ) and effective optical path length (L_A)

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

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

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

3.7

opacimeter

instrument used for the measurement of smoke characteristics using the optical method of transmittance

3.7.1

full-flow opacimeter

instrument in which all flow of exhaust gas passes through the smoke measuring chamber

3.7.1.1

full-flow end-of-line opacimeter

instrument which measures the opacity of the full exhaust plume as it exits the tailpipe

NOTE The light source and receiver for this type of opacimeter are located on opposite sides of the smoke plume and in close proximity to the open end of the tailpipe. When applying this type of opacimeter, the effective optical path length is a function of the tailpipe design.

3.7.1.2

full-flow in-line opacimeter

instrument which measures the opacity of the full exhaust plume within the tailpipe

NOTE The light source and receiver for this type of opacimeter are located on opposite sides of the smoke plume and in close proximity to the outer wall of the tailpipe. With this type of opacimeter the effective optical path length is dependent on the instrument.

3.7.2

partial-flow opacimeter

instrument which samples a representative portion of the total exhaust flow and passes the sample through the measuring chamber

NOTE With this type of opacimeter the effective optical path length is a function of the opacimeter design.

3.7.3

Opacimeter response time

3.7.3.1

opacimeter physical response 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 of the gas being measured is changed in less than 0,01 s

NOTE The physical response time of the partial flow opacimeter is defined with the sampling probe and transfer tube. Additional information on the physical response time can be found in 8.2.1 and 11.7.2 of ISO 11614:1999.

3.7.3.2

opacimeter electrical response 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 Additional information on the electrical response time can be found in 8.2.3 of ISO 11614:1999.

4 Symbols and units

See Table 1.

Table 1 — Symbols and units for terms used in this part of ISO 8178

Symbol	Term	Unit
B	Bessel function constant	1
C	Bessel function constant	1
D	Bessel function constant	1
E	Bessel constant	1
f_a	Atmospheric factor	1
f_c	Bessel filter cut-off frequency	s ⁻¹
k	Light absorption coefficient	m ⁻¹
k_{corr}	Ambient condition corrected light absorption coefficient	m ⁻¹
k_{obs}	Observed light absorption coefficient	m ⁻¹
K	Bessel constant	1
K_s	Smoke ambient correction factor	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 effective mean pressure	kPa
p_s	Dry atmospheric pressure	kPa
P	Engine power	kW
S_i	Instantaneous smoke value	m ⁻¹ or %
t_{Aver}	Overall response time	s
t_e	Opacimeter electrical response time	s
t_F	Filter response time for Bessel function	s
t_p	Opacimeter physical response time	s
Δt	Time between successive smoke data (= 1/sampling rate)	s
T_a	Engine intake air temperature	K
X	Desired overall response time	s
Y_i	Bessel averaged smoke value	m ⁻¹ or %
ρ	Dry ambient density	kg/m ³
τ	Smoke transmittance	%
Ω	Bessel constant	1

5 Test conditions

5.1 Ambient test conditions

5.1.1 Test condition parameter

The absolute temperature T_a , of the engine intake air expressed in kelvin, and the dry atmospheric pressure p_s , expressed in kPa, shall be measured, and the atmospheric factor f_a , shall be determined using Formulae (3) to (5).

For naturally aspirated and mechanically supercharged compression-ignition engines and compression-ignition engines with wastegates operating:

$$f_a = \left(\frac{99}{p_s} \right) \times \left(\frac{T_a}{298} \right)^{0,7} \quad (3)$$

This formula also applies if the wastegate is operating only during sections of the test cycle. If the wastegate is not operating during any section of the test cycle, Formula (4) or (5) shall be used depending on the type of charge cooling, if any.

For turbocharged compression-ignition engines without charge air cooling, or with charge air cooling by air/air cooler:

$$f_a = \left(\frac{99}{p_s} \right)^{0,7} \times \left(\frac{T_a}{298} \right)^{1,2} \quad (4)$$

For turbocharged compression-ignition engines with charge air to liquid charge air cooler:

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

5.1.2 Test validation criteria — test conditions

For a test to be recognized as valid the parameter f_a should be such that:

$$0,93 \leq f_a \leq 1,07 \quad (6)$$

It is recommended that tests be with the parameter f_a between 0,96 and 1,06.

Additional validation criteria are given in 7.3.2.3 and A.3.2.2.

5.2 Power

Those auxiliaries which are necessary only for the operation of the machine and which may be mounted on the engine shall be removed for the test. The following incomplete list is given as an example:

- air compressor for brakes;
- power steering pump;
- air conditioning compressor;
- pumps for hydraulic actuators.

For further details see 3.8 of ISO 8178-1:2006.

5.3 Engine air inlet system

The test engine shall be equipped with an air inlet system presenting an air inlet restriction within $\pm 10\%$ of the manufacturer's specified upper limit for a clean air-cleaner. The upper limit shall be at the engine operating condition, as specified by the manufacturer, that results in the maximum air flow for the respective engine application.

5.4 Engine exhaust system

The test engine shall be equipped with an exhaust system presenting an exhaust back pressure within $\pm 10\%$ of the manufacturer's specified upper limit. The upper limit shall be at the engine operating condition, as specified by the manufacturer, that results in the maximum declared power for the respective engine application. Tests may be conducted with a muffler, as this will tend to reduced exhaust pulsations which may interfere with measurement of smoke. Further, the use of a muffler should provide better correlation between test-bed smoke measurement and any in-field smoke tests that may occur. The design of the muffler (i.e. volume) should be typical of that used in actual field applications of the engine being tested.

5.5 Cooling system

An engine cooling system with sufficient capacity to maintain the engine at normal operating temperatures prescribed by the manufacturer shall be used.

5.6 Lubricating oil

Specifications of the lubricating oil used for the test shall be recorded and presented with the results of the test.

5.7 Engines with charge air cooling

The temperature of the cooling medium and the temperature of the charge air shall be recorded.

The cooling system shall be set with the engine operating at the speed and load specified by the manufacturer. The charge air temperature and cooler pressure drop shall be set to within $\pm 4\text{ K}$ and $\pm 2\text{ kPa}$ respectively of the manufacturer's specification.

5.8 Test fuel temperature

The test fuel temperature shall be in accordance with the manufacturer's recommendations. In the event that the manufacturer does not specify the temperature, it shall be $311\text{ K} \pm 5\text{ K}$. Except for cases where "heavy" fuel is used, the temperature specified by the manufacturer shall not be greater than 316 K . The fuel temperature shall be measured at the inlet to the fuel injection pump unless otherwise specified by the manufacturer, and the location of measurement shall be recorded.

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. Where fuels designated in ISO 8178-5 are used as reference fuels, the reference code and the analysis of the fuel shall be provided. For all other fuels the characteristics to be recorded are those listed in the appropriate universal data sheets in ISO 8178-5.

The selection of the fuel for the test depends on the purpose of the test. Unless otherwise agreed by the parties the fuel shall be selected in accordance with Table 2. When a suitable reference fuel is not available, a fuel with properties very close to the reference fuel may be used. The characteristics of the fuel shall be declared.

Table 2 — Selection of fuel

Test purpose	Interested parties	Fuel selection
Type approval (certification)	Certification body Manufacturer or supplier	Reference fuel, if one is defined Commercial fuel if no reference fuel is defined
Acceptance test	Manufacturer or supplier Customer or inspector	Commercial fuel as specified by the manufacturer ^a
Research/development	One or more of: — manufacturer; — research organization; — fuel and lubricant supplier; etc.	To suit the purpose of the test
^a Customers and inspectors should note that the emission tests carried out using commercial fuel will not necessarily comply with limits specified when using reference fuels. The fuel used for acceptance tests should be within the range of fuel specifications allowed by the engine manufacturer, as specified in the engine manufacturer's technical literature.		

7 Measurement equipment and accuracy

7.1 General

The following equipment shall be used for smoke tests on engines using dynamometers. This part of ISO 8178 does not contain details of pressure and temperature measuring equipment. Instead, only the accuracy requirements of such equipment necessary for conducting a smoke test are given in 7.4.

7.2 Dynamometer specification

An engine dynamometer with adequate characteristics to perform the test cycle as described in Annexes A and B shall be used. Test cycle linearity requirements apply only when tests have been conducted using an electric dynamometer. The instrumentation for torque and speed measurement shall allow the measurement accuracy required for running the test cycle within the limits given in Annexes A and B. Speed and torque shall be sampled at a frequency of at least 1 Hz. The accuracy of the measuring equipment shall be such that the maximum tolerances of the figures given in Table 3 are not exceeded. Engine driven equipment that meets these requirements may be used instead of dynamometers.

7.3 Determination of smoke

7.3.1 General

Transient smoke tests must be conducted using opacimeter-type smokemeters. Three different types of opacimeters are allowed: in-line and end-of-line full-flow opacimeters and the partial-flow opacimeter. Specifications for the three types of opacimeters can be found in Clause 11 of this part of ISO 8178 and in Clauses 6 and 7 of ISO 11614:1999. Temperature correction has not been validated for transient tests, therefore, temperature correction of smoke results has not been included in this part of ISO 8178.

Table 3 — Permissible deviations of instruments for engine-related parameters

Item	Permissible deviation (% based on engine maximum values) in accordance with ISO 3046-3	Calibration intervals months
Engine speed	± 2 %	3
Torque	± 2 % or ± 5 Nm ^a	3
Power	± 3 %	not applicable
^a Whichever is greater.		

7.3.2 Specifications — opacimeters

7.3.2.1 General

Smoke tests require the use of a smoke measurement and data processing system which includes three functional units. These units may be integrated into a single component or provided as a system of interconnected components. The three functional units are as follows:

- a full-flow or a partial-flow opacimeter meeting the specifications of this subclause. Detailed specifications for opacimeters can be found in Clause 11 and in ISO 11614;
- a data processing unit capable of performing the functions described in 10.2 and 10.3 and in Annex D;
- a printer and/or electronic storage medium to record and output the required smoke values specified in Annexes A and B.

7.3.2.2 Linearity

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

7.3.2.3 Zero drift

Zero drift during the lesser of a one hour period or the duration of the test shall not exceed $\pm 0,5$ % opacity or 2 % of full scale whichever is smaller.

7.3.2.4 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.

7.3.2.5 Instrument response time

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

7.3.2.6 Sampling requirements for partial-flow opacimeters

The sampling conditions shall conform to the requirements of 11.3.

7.3.2.7 Light source

The light source shall conform to the requirements of 11.2 and 11.3

7.3.2.8 Neutral density filters

Any neutral density filters used for calibrating and checking opacimeters must be known to an accuracy of ± 1 % opacity and the filter's nominal value must 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.

7.4 Accuracy

The calibration of all measuring instruments shall be traceable to International Standards (or national standards if no International Standards exist) and comply with the requirements given in Table 3.

8 Calibration of the opacimeter

8.1 General

The opacimeter shall be calibrated as often as necessary in order to fulfil the accuracy requirements of this part of ISO 8178. The calibration method that shall be used is described in 8.2.

8.2 Calibration procedure

8.2.1 Warming-up time

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

8.2.2 Establishment of the linearity response

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

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

The linearity of the opacimeter, when used in the opacity mode, shall be checked periodically in accordance with the manufacturer's recommendations. A neutral density filter between 30 % and 60 % opacity which meets the requirements of 7.3.2.8 shall be introduced to the opacimeter and the value recorded. The instrument readout must not differ by more than ± 2 % opacity from the nominal value of the neutral density filter. Any nonlinearity exceeding the above value shall be corrected prior to the test.

9 Test run

9.1 Installation of the measuring equipment

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. Additionally, the requirements of Clause 10 of ISO 11614:1999 shall be observed, where appropriate.

9.2 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 sooting of the meter 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. The light absorption coefficient is then correctly calculated based upon the measured opacity and L_A , as submitted by the opacimeter manufacturer, when the instrument is returned to the k readout mode for testing.

With no blockage of the opacimeter light beam, the readout shall be adjusted to 0 % $\pm$ 1 % opacity. With the light being prevented from reaching the receiver, the readout shall be adjusted to 100 % $\pm$ 1 % opacity.

9.3 Test cycle

The engine shall be run on the test cycle as described in Annexes A, B, E and F, taking into account the considerations noted in Annex C.

9.4 Determination of effective optical path length (L_A)

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 smokemeter 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 smokemeter is essentially the same as the tailpipe outlet along the line of orientation of the smokemeter 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 $\pm$ 2 % opacity, determination of L_A shall be made within $\pm$ 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.) For the smallest standard effective optical path length (0,038 m), $\pm$ 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 more easily measured.

10 Data evaluation and calculation

10.1 Data evaluation

10.1.1 General requirements – opacimeters

The smoke shall be sampled using a minimum frequency of 20 Hz. Smoke values shall be reported in units of either opacity (N) or light absorption coefficient (k). The measured smoke values (transmittance) shall be converted into the respective smoke units and corrected for opacimeter optical path length differences, as necessary (see 10.1.2, 10.1.3 and 10.1.4). Ambient density correction, if necessary, shall be applied to the light absorption coefficient, only (see 10.3). The smoke data shall then be processed by means of the Bessel algorithm, as described in 10.2 and Annex A.

The sample line length shall not affect the smoke trace (see 10.3). 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 transport of smoke in the exhaust system.

The smoke values shall then be calculated as described in Annex A.

10.1.2 Beer-Lambert relationships

The Beer-Lambert law defines the relationship between transmittance, light absorption coefficient and effective optical path length as shown in Formula (7).

$$\frac{\tau}{100} = e^{-kL_A} \quad (7)$$

From the definitions of transmittance and opacity, the relationship between these parameters may be defined as shown in Formula (8).

$$N = 100 - \tau \quad (8)$$

From Formulae (7) and (8) the following relationships are derived:

$$N_{AS} = 100 \times \left[1 - \left(1 - \frac{N_A}{100} \right)^{\frac{L_{AS}}{L_A}} \right] \quad (9)$$

$$k = -\frac{1}{L_A} \times \ln \left(1 - \frac{N_A}{100} \right) \quad (10)$$

10.1.3 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 (8). For most opacimeters this step is done internally and is invisible 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 (9) must 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 and this secondary conversion step is not required.

If the test results are reported in units of light absorption coefficient, then Formula (10) shall be applied.

10.1.4 Effective optical path length input values

In order to apply Formula (10), it is necessary to apply the as-measured effective optical path length (L_A). To use Formula (9), 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 straight tailpipes with a circular cross section, L_A is equal to the tailpipe inner diameter.

For partial-flow (sampling) 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 must 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 4. Smoke opacity may be measured at non standard optical path lengths.

For the purposes of Table 4 engine power need not be measured. Engine power is typically available either from a label on the engine, from the owner's manual for the engine or from information used to apply certification or type approval of the engine. In the event that 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 4 — Standard effective optical path lengths

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

10.2 Bessel algorithm

10.2.1 General

The Bessel algorithm shall be used to compute the average values from the instantaneous smoke readings. The algorithm can be applied to either values of smoke opacity or light absorption coefficient. However, if the smoke level is less than 40 % opacity, the algorithm may be applied to the opacity signal with negligible error. 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 response time of the opacimeter system and the sampling rate. Therefore, the calculations given in 10.2.2 must be repeated whenever the system response time and/or sampling rate changes.

10.2.2 Calculation of filter response time and Bessel constants

The required Bessel filter response time (t_F) is a function of the physical and electrical response times of the opacimeter system, as defined in 3.7.3, and the desired overall response time X and shall be calculated using Formula (11):

$$t_F = \sqrt{X^2 - (t_p^2 + t_e^2)} \quad (11)$$

where

t_p is the physical response time, in seconds;

t_e is the electrical response time, in seconds.

Formula (11) can be used to adjust differing opacimeters to a common response time provided that both t_p and t_e are $\ll X$ (see 7.3.2.5) and provided that both t_p and t_e are $\ll$ the duration of the transient test.

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 D). The response time is defined as the time between when the Bessel output reaches 10 % (t_{10}) and