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Measurement of road tunnel air quality

Mesurage de la qualité de l'air d'un tunnel routier

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Foreword

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

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

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

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

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

This document was prepared by Technical Committee ISO/TC 146, *Air quality*, Subcommittee SC 3, *Ambient atmospheres*.

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

The objective of this document is to provide road tunnel owners and operators with standard methods for checking and calibrating instruments used in road tunnels to continuously monitor air speed, carbon monoxide (CO), nitric oxide (NO) and nitrogen dioxide (NO_2) concentrations and visibility.

Data from these instruments enables tunnel operators to manage the ventilation system in real time or to take emergency measures (e.g. closure to traffic).

This document has been developed as a performance-based standard that allows for use of a number of direct-reading instruments. Statements expressed in mandatory terms in notes to tables and figures are deemed to be requirements of this document.

In order to improve traffic flow in central business districts and through sensitive environments, road tunnels are increasingly used throughout the world to achieve the desired outcomes. There are a large number of tunnels in operation, with a number of others in the planning stages.

Road tunnel projects are subject to environmental and/or planning approval conditions by regulatory authorities that specify the parameters to be monitored in-tunnel, typically including air speed, CO, NO, NO_2 and visibility, with NO measured as a surrogate for NO_2, with, historically, 10 % of total nitrogen oxides assumed to be NO_2. However, this assumption is no longer considered appropriate, given the increased proportion of diesel fuelled vehicles in vehicle fleets. It can also be a requirement that the tunnel ventilation system is controlled to:

a) reduce CO and NO_2 concentrations within the tunnel environment to enable conformance with in-tunnel air quality criteria for various averaging periods;

b) prevent or reduce portal emissions and resultant environmental impacts;

c) ensure appropriate visibility for different tunnel operating conditions; and

d) control smoke and improve the self-rescue time and security of tunnel users in emergency situations such as fires.

Conformance with in-tunnel air quality criteria is typically determined by averaging measured CO and measured or estimated NO_2 concentrations from a number of instruments located on possible travel paths throughout the tunnel system.

The number of instruments required to adequately characterise the tunnel environment is dependent on a number of factors, including:

a) tunnel length and number of gradient changes and entry and exit ramps;

b) volume of traffic and types of vehicles;

c) exhaust ventilation system flowrate and control regime; and

d) regulatory requirements.

Consequently, this aspect is not addressed in this document. It is noted, however, that computational fluid dynamics modelling can be used as a design tool to assist in the placement of instruments, ensuring that indicative maximum and average concentrations are measured.

Measurement of road tunnel air quality

1 Scope

This document describes methods for determining air speed and flow direction, CO, NO and NO_2 concentrations and visibility in road tunnels using direct-reading instruments. This document specifically excludes requirements relating to instrument conformance testing.

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 5802, *Industrial fans — Performance testing in situ*

ISO 6145, *Gas analysis — Preparation of calibration gas mixtures using dynamic methods*

ISO 10780, *Stationary source emissions — Measurement of velocity and volume flowrate of gas streams in ducts*

ISO/IEC Guide 98-3, *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

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
calibration
set of operations that establish, under specified conditions, the relationship between the value indicated by a measuring instrument and the corresponding known value of a reference standard

3.2
certified reference material
reference material, characterized by a metrologically valid procedure for one or more specified properties, accompanied by a reference material certificate that provides the value of the specified property, its associated uncertainty, and a statement of metrological traceability

3.3
check
confirmation of acceptable instrument response, without adjustment

3.4
fall time
time interval, after a step decrease in input concentration, between initial instrument response and 10 % of initial instrument response

3.5
full scale
FS
nominated maximum concentration for which an instrument has been calibrated

Note 1 to entry: The full scale (FS) is selected to cover the normal range of values expected in the sampling environment.

3.6
interference equivalent
positive or negative instrument response caused by a substance other than the one being measured

3.7
linearity
deviation of an instrument's output from a linear best fit line when subjected to varying reference test atmospheres

3.8
lower detectable limit
minimum pollutant concentration that produces a signal of exactly three times the repeatability standard deviation

Note 1 to entry: See ISO 5725-1.

3.9
parameter
one of the characteristics related to an air sample

EXAMPLE Concentration of pollutant or other quantifiable property (e.g. air speed).

3.10
ppm
parts per million
ratio expressing the volume of gaseous pollutant contained in 1 000 000 volumes of atmosphere

Note 1 to entry: It may be expressed in terms of millilitres per cubic metre as the values are identical. Alternatively, it is one million times the ratio of the partial pressure of gaseous pollutant to the pressure of the atmosphere in which it is contained.

3.11
precision
variation about the mean of repeated measurements of the same pollutant concentration on the same instrument, expressed as one standard deviation about the mean

3.12
range
nominal minimum and maximum concentrations that a method is capable of measuring

Note 1 to entry: The nominal range is specified by the lower and upper range limits in concentration units, e.g. 0 to 250 ppm.

3.13
reference test atmosphere
test atmosphere containing a known concentration of pollutant, typically generated by diluting the contents of a cylinder containing a gaseous *certified reference material* (3.2)

3.14
rise time
time interval, after a step increase in input concentration, between the instrument initial response and 90 % of the final instrument response

3.15
road tunnel
any fully enclosed length of roadway with a minimum length ranging between 90 m and 150 m

EXAMPLE National Fire Protection Association and UK Design Manual for Roads and Bridges.

3.16
span drift
percentage change in the instrument response to an on-scale pollutant concentration over a period of continuous unadjusted operation

3.17
U_{95}
measurement of expanded uncertainty at a confidence interval of 95 % according to ISO/IEC Guide 98-3

3.18
zero air
air free from contaminants likely to cause a detectable response on the test instrument

3.19
zero drift
change in the instrument response to a zero-pollutant concentration over a period of continuous unadjusted operation

4 Test parameter — Air speed and flow direction

4.1 General

Clause 4 describes continuous, direct-reading instruments for determining air speed and flow direction in road tunnels. Providing the instrument performance is within the specifications given in Table 1, alternate methods may be used within the context of this document.

4.2 Principle

Air speed and flow direction in modern road tunnels are typically measured using ultrasonic flow sensors.

Ultrasonic sensor systems are based on the principle that the speed of air movement changes the transit time of a sound pulse across a fixed distance, allowing calculation of the air speed and determination of flow direction.

Instrument outputs may be used to control mechanical ventilation in a tunnel during both routine and emergency operation.

The measurement of flow in road tunnels is important for emergency operation (e.g. vehicle fire), enabling the control of air flow such that fumes are not dispersed in the tunnel tube. The choice of cross section or single point air flow measurements for this purpose is dependent on local technical practices.

Air flow measurement can also be important for the management of mechanical ventilation, either to dilute pollutants, or to control the atmospheric discharges at the portals.

Ultrasonic sensors are either open path or single point instruments, installed at various locations along the tunnel length, including portals and exit ramps.

Open path ultrasonic flow sensors measure the average value over the tunnel width, with transceiver pairs installed on opposing walls at an angle of 45° to 60° to the tunnel axis. In order to eliminate potential measurement errors caused by variations in ultrasonic sound speed due to temperature and pressure, the transceiver units shall be installed on each side of the tunnel wall, with the transit time measured in both directions.

Single point ultrasonic flow sensors use the same measurement principle as open path sensors, measuring changes in the transit time of a sound pulse across a fixed distance, but in this case the distance evaluated is within the instrument casing.

NOTE Open path ultrasonic flow sensors are typically located high on tunnel walls; consequently, it is possible that the measured air speed is not representative of the average speed for the overall tunnel cross-section. Similarly, single point ultrasonic flow sensors measure air speed close to the tunnel wall (or ceiling) and nearer the pavement, consequently it is possible that the measured air speed is not representative of the average speed for the tunnel cross-section, with the added potential, under normal operating conditions, for increased error due to turbulence created by vehicular traffic.

4.3 Apparatus

4.3.1 Instrument

A continuous direct-reading instrument that meets or exceeds the specifications given in Table 1. The manufacturer's published performance specifications shall be deemed as acceptable evidence of conformance to the given requirements, if accompanied by a statement of measurement uncertainty issued by an organization that meets the requirements of ISO/IEC 17025.

Table 1 — Instrument performance specifications for tunnel air speed systems

Parameter	**Minimum requirements**
Range	(−20 to 20) m/s
Expanded measurement uncertainty	2 % of reading or 0,2 m/s[a]
Resolution	≤ 0,1 m/s
[a] Whichever is the greater.	

4.3.2 Reference path length measurement device (open path instruments only)

A metrologically traceable reference path length measurement device with an uncertainty of 0,5 % U_{95} is required to make an accurate determination of the path length. The reference path length measurement device shall be checked over a path length of at least the instrument measurement path length.

Organizations performing the tests outlined in this clause shall meet the requirements of ISO/IEC 17025.

4.3.3 Transfer standard flow sensor

A metrologically traceable hand-held vane or hot-wire anemometer, or equivalent, of similar or higher specification to the air speed sensor, with an uncertainty of 2 % U_{95} is required to check the operation of air speed sensors. The transfer standard flow sensor shall be calibrated over a range exceeding the maximum air flow experienced in the tunnel.

Organizations performing the tests outlined in this clause shall meet the requirements of ISO/IEC 17025.

4.4 Procedure

The procedure shall be as follows:

a) For open path ultrasonic flow sensors, ensure that the transceivers are installed such that the path for the sonic pulse is unimpeded by tunnel equipment or other obstructions, including vehicular traffic, whilst allowing ease of access for instrument maintenance and calibration.

b) For open path ultrasonic flow sensors check instrument horizontal and vertical alignment and beam angle, in accordance with the manufacturer's instructions.

c) For open path ultrasonic flow sensors, accurately measure and record the distance between the transceivers using a reference path length measurement device (4.3.2).

d) Set up the instrument and carry out initial checks in accordance with the manufacturer's instructions (e.g. setting the path length, configuring and scaling of analogue outputs, setting of alarm values and level of damping) and the requirements of 4.5.

e) Take measurements in accordance with the manufacturer's instructions and ensure that the values obtained relate to the correct date and time.

4.5 Instrument checks and calibrations

4.5.1 General

Calibration of an instrument establishes the quantitative relationship between the air speed and the instrument's response.

Instrument checks and calibrations shall be carried out in accordance with the frequencies specified by the equipment manufacturer and in accordance with Table 2.

In addition, operational precision checks shall be carried out as follows:

a) Prior to decommissioning or physical relocation of the instrument, if operational.

b) Following physical relocation of the instrument.

c) After any repairs that might affect the instrument's response.

d) Upon any indication of an instrument malfunction or change in response that may cause the instrument to drift by more than the values given in Table 2.

NOTE 1 The air flow and direction monitor can incorporate an automatic daily zero and span check function for daily quality control and assurance purposes.

NOTE 2 Checks and calibrations specified in this section can be omitted if the air flow measuring instrument provides proven equivalent self-test functions (e.g. read back of analogue or digital outputs).

4.5.2 Measurement path length (open path instruments only)

The measurement path length for open path ultrasonic flow sensors is normally defined as the distance between the faces of opposing transceiver units, however, this should be confirmed with the manufacturer. The measurement path length shall be determined upon installation (see Table 2) using a reference distance measurement device as described in 4.3.2.

A check of the measurement path length shall also be conducted whenever an open path instrument is reinstalled following maintenance or repair, if the maintenance or repair could result in a change of measurement path length.

4.5.3 Initial check

Conduct an initial check on the ultrasonic flow sensor prior to road tunnel opening using a collocated transfer standard (CTS) method at a minimum of three air velocities (if technically feasible) evenly spread over the tunnel design operational range.

For open path ultrasonic flow sensors, measurements shall be taken at a minimum of two points per trafficable lane over the measurement path. For a single point ultrasonic flow sensor, the CTS needs to be within 1 m of the subject sensor in the horizontal and 0,5 m in the vertical, but the same distance from the tunnel wall.

The CTS method requires a calibrated hand-held vane or hot-wire anemometer, or equivalent, of similar or higher specification to the ultrasonic flow sensor, located in the vicinity of the measurement path for the sensor being assessed.

For both single point and open path ultrasonic flow sensors it is important to site the CTS to be representative of the air flow at the subject sensor, without interfering with either instrument's response.

The procedure shall be as follows:

a) Ensure that the CTS is oriented such that the reading is obtained in the direction of air flow.

b) Connect the CTS to an independent data logger. Once the air speed has stabilised, record check data for a period of not less than 5 min. Simultaneously record the response from the in-situ sensor over the same period.

c) Average the recorded data over the selected period, and, if applicable, across all CTS measurement points. Calculate the difference between the in-situ sensor and CTS average readings.

d) Check that the difference conforms to the tolerance given in Table 2. If the result is not within the prescribed tolerance, review siting and site-specific issues, conduct repairs and/or instrument calibrations as required and repeat the above procedure until compliance with the specified tolerance is indicated.

4.5.4 Cross-section calibration

A correlation may also be required between the ultrasonic flow sensor output and the total ventilation system flowrate, in order to obtain a factor or algorithm for use in the tunnel ventilation control system.

If required, the cross-section calibration shall be performed following instrument commissioning and after the initial check (4.5.3) has been conducted.

The total ventilation system flowrate may be determined by measuring air speeds across the tunnel cross-section, at approximately the same tunnel longitudinal position as the ultrasonic flow sensor, using a calibrated hand-held vane or hot-wire anemometer, or equivalent, of similar or higher specification to the ultrasonic flow sensor.

In this instance, the number and location of measurement points across the tunnel cross-section will be dependent on the hydraulic diameter and shape of the tunnel cross-section. Methods typically used are the tracer gas method, the equal area method described in ISO 10780 and the Log-Tchebycheff method described in ANSI/ASHRAE Standard 41.2 and ISO 5802. The average measured speed is multiplied by the cross-sectional area in order to calculate the total ventilation system flowrate.

Measurement of the total ventilation system flowrate does not preclude the need to check the actual instrument response in accordance with the procedure described above. It should also be recognised that the correlation determined between total ventilation system flowrate and ultrasonic flow sensor output in an empty tunnel may not reflect what occurs in an operational tunnel.

4.5.5 Zero check

If a zero-air flow environment can be attained, the zero response of the ultrasonic flow sensor shall be checked on a yearly basis, in accordance with the manufacturer's instructions.

For single point sensors this can be readily achieved by enclosing the sensor in a box which isolates it from any draughts.

Check that the zero response is within the tolerance given in Table 2. If the result is not within the tolerance, conduct repairs and/or instrument calibrations as required and repeat the procedure until the zero response is within the tolerance.

4.5.6 System component check

Cables, recorders, signal conditioning and data processing devices can corrupt the sensor's output.

A system component check shall be conducted on a yearly basis to ensure the transmitted sensor output matches that received at the data recording device. For example, if the ultrasonic flow sensor gives a 20 mA output with an air speed of 20 m/s, then apply a 20 mA signal to the system to confirm that 20 m/s is indicated at the data recording device.

Check that the response is within the tolerance given in Table 2. If the response is not within the tolerance, conduct repairs and/or instrument calibrations as required and repeat the procedure until the response is within the tolerance.

4.5.7 Operational precision check

An operational precision check shall be conducted on the ultrasonic flow sensor on a yearly basis using the CTS method at a minimum of one air speed, and, for open path ultrasonic flow sensors, a minimum of three equally spaced points over the measurement path. For a single point ultrasonic flow sensor, the CTS shall be within 1 m of the subject sensor in the horizontal and 0,5 m in the vertical, but the same distance from the tunnel wall.

The CTS method requires a calibrated hand-held vane or hot-wire anemometer, or equivalent, of similar or higher specification to the ultrasonic flow sensor, located in the same horizontal plane as the measurement path for the sensor being assessed.

The transfer standard sensor shall be routinely calibrated by a recognized external authority such that the CTS is traceable to required reference standards. This calibration shall be evidenced by a calibration certificate which states the sensitivity of the device by a procedure which establishes traceability to a recognized standard and for which a measurement uncertainty is given at a stated level of confidence, and the period during which the calibration is valid.

For both single point and open path ultrasonic flow sensors it is important to site the CTS to be representative of the air flow at the subject sensor, without interfering with either instrument's response.

The procedure shall be as follows:

a) Ensure that the CTS is oriented such that the reading is obtained in the direction of air flow.

b) Connect the CTS to an independent data logger. Record check data for a sufficient period that demonstrates a stable response. Simultaneously record the response from the in-situ sensor over the same period.

c) Average the recorded data over the selected period, and, if applicable, across the three CTS measurement points. Calculate the difference between the in-situ sensor and CTS average readings.

d) Check that the difference conforms to the tolerance given in Table 2. If the result is not within the prescribed tolerance, conduct repairs and/or instrument calibrations as required and repeat the above procedure until compliance with the specified tolerance is indicated.

Table 2 — Instrument check and calibration requirements for tunnel air speed systems

Parameter	Criterion	Frequency
Measurement path length	± 0,5 %	Initial[b]
Initial check	2 % of reading or ± 0,2 m/s[a]	Initial
Zero check	± 0,2 m/s	≤ 12 months
System component check	± 0,2 % FS	≤ 12 months
Operational precision check	6 % of reading or ± 0,3 m/s[a]	≤ 12 months

[a] Whichever is the greater.

[b] And after maintenance or repair (if this could result in a change to measurement path length)

A detailed log of all performance checks and calibration undertaken shall be maintained.

4.6 Maintenance

4.6.1 General

Maintenance should be carried out in accordance with the frequencies specified in Table 3. Manufacturers may require additional procedures.

A detailed log of all performance checks and maintenance undertaken shall be maintained and retained with the initial check air speed and flow direction data.

The maintenance regime recommended in this clause is for preventive maintenance, with the maintenance components and frequencies recommended minimums. When the manufacturer makes claims regarding maintenance intervals that exceed these minimum requirements, they shall be deemed as acceptable if accompanied by a certificate issued from an organization other than the equipment manufacturer that meets the requirements of ISO/IEC 17025.

NOTE Condition based maintenance or predictive maintenance can be used as alternative regimes, given that these systems determine differing maintenance components and frequencies.

4.6.2 On site checks

Maintenance should be carried out in accordance with the frequencies specified in Table 3. Visual examination of the ultrasonic flow sensors should be conducted on a six-monthly basis. A log of the results of such checks shall be maintained, with routine entries providing the evidence of attendance needed to support data validity claims.

Table 3 — Routine maintenance for tunnel air speed systems

Maintenance component	Frequency
Visual inspection	≤ 6-months
Sensor cleaning[a]	≤ 12-months
Alignment check	≤ 12-months

[a] Dependent on manufacturer's specifications and how quickly the sensor gets dirty.

Routine maintenance may include the removal of dirt, bird nests and cobwebs and the checking of transceiver alignment. The maintenance interval is dependent on air quality in the tunnel, but should not exceed 12 months. Care should be taken when cleaning ultrasonic flow sensor components, in accordance with manufacturer's recommendations.

Compressed air should not be used for cleaning ultrasonic flow sensor components.

When establishing a schedule for on-site checks the following should be considered:

a) A plot of collected data will indicate how the sensor is performing (e.g. control chart as per ISO 7870-1).

b) Faults may be indicated by an incorrect zero, an unstable instrument response (which may be evident at low air velocities), low sensitivity (at low air velocities) and low variability of the recorded air velocities.

c) Data inter-comparisons between other sensors located within the tunnel.

4.7 Calculation and expression of results

Results shall be expressed in units of metres per second. The positive or negative sign of the speed, with respect to traffic flow or portal flow, shall be clearly defined in the report.

4.8 Measurement uncertainty

The measurement uncertainty of this method will vary for each installation. Factors affecting the overall uncertainty include how representative the ultrasonic flow sensor output is of the tunnel cross sectional area.

As a guide, measurement uncertainties for air speeds corresponding to the greater of ± 0,2 m/s or 2 % of reading can be achieved using modern equipment. In all cases, the measurement uncertainty shall be determined based on individual laboratory practices.

NOTE A suitable method for calculating measurement uncertainty can be found in ISO/IEC Guide 98-3.

5 Test parameters — Carbon monoxide, nitric oxide and nitrogen dioxide

5.1 General

Clause 5 describes continuous, direct-reading instruments for determining CO, NO and NO_2 concentrations in road tunnels. Providing the instrument performance is within the specifications given in Table 4, alternate methods may be used within the context of this document.

5.2 Principle

CO and NO concentrations in road tunnels are typically measured using open path infra-red instruments and single point electrochemical sensors. Electrochemical sensors are often preferred due to the low cost of installation and maintenance. One of the major purposes of monitoring CO concentrations in road tunnels is to detect fire situations, particularly at the beginning of an event, during the user evacuation phase.

NO_2 concentrations in road tunnels are typically measured using open path ultra-violet or DOAS (differential optical absorption spectroscopy) instruments or single point electrochemical sensors.

Other measurement techniques, including extractive systems and ambient air quality analysers, may also be used provided they meet the instrument performance specifications contained in either this document or other applicable standards, for example ISO 4224, ISO 7996, EN 14211 and EN 14626. Tunnel safety requirements relating to handling, storage and transport of compressed gases also need to be considered.

Open path infra-red instruments are based on gas filter correlation technology with measurement path lengths normally ranging from 3 m (6 m folded beam) to 10 m (single beam).

Unlike ultrasonic flow sensors, the open path instrument transmitter and receiver, or transceiver and retroreflector, are typically mounted on the wall on the same side of the tunnel, preventing potential glare impacts on tunnel users from the light beam.

The open path measurement technique for all pollutants is based on the Beer-Lambert Law, which relates the absorption of light as a function of the concentration of the absorbing species, the absorption characteristics of that species, and the length of the absorption path.

The Beer-Lambert Law in this instance can be expressed mathematically as given in Formula (1):

$$I(\lambda)=I_0(\lambda)e^{-\sum c_i a_i(\lambda)L} \quad (1)$$

where

$I(\lambda)$ is the measured light intensity at a specific wavelength λ;

$I_0(\lambda)$ is the light intensity at a specific wavelength λ without any absorption;

c_i is the concentration of gaseous species i;

$a_i(\lambda)$ is the absorption cross-section at wavelength λ for gaseous species i (quantifies the probability for light absorption at each wavelength; units are m^2 per molecule, m^2 per µg, or similar, depending on the unit of concentration);

L is the optical path length.

An electrochemical sensor consists of a capillary diffusion barrier, a hydrophobic membrane and working and counter electrodes separated by a thin layer of electrolyte. The pollutant passes through the capillary barrier, diffuses across the hydrophobic membrane and reacts at the surface of the working electrode.

As the process is diffusion controlled, the instrument response is directly proportional to the pollutant concentration, in accordance with Formula (2):

$$R = D \times F \times c_i \times A/t \times e \tag{2}$$

where

R is the instrument response;

D is the diffusion coefficient;

F is the Faraday constant;

c_i is the concentration of gaseous species i;

A is the membrane area;

t is the membrane thickness;

e is the number of electrons.

In general, the limitations of electrochemical sensors include their response to temperature, relative humidity and interferent gases, however, some instruments incorporate a temperature sensor to correct the instrument response using a proprietary algorithm.

A specific limitation for measurement of NO_2 using electrochemical sensors is that constant exposure to non-negligible NO_2 concentrations can rapidly saturate the electrolyte, requiring frequent cell replacement.

5.3 Apparatus

5.3.1 Instrument

The instrument is a continuous direct-reading instrument that meets the performance specifications given in Table 4. The instrument may be used over any range within the limits of this document, provided it has been calibrated and checked in accordance with 5.5.

The manufacturer's published performance specifications shall be deemed as acceptable evidence of conformance to the given requirements, if accompanied by a statement and test report of measurement uncertainty issued by an organization that meets the requirements of ISO/IEC 17025.

Instruments can have cross sensitivities to a range of substances that may be present in road tunnels, including the components to be measured (e.g. NO). This aspect should be considered when selecting equipment. An interference equivalent corresponding to less than ± 0,5 % FS is a requirement of this document for each relevant interferent gas applied to the instrument at typical concentrations present in the tunnel atmosphere.

Table 4 — Instrument performance specifications for tunnel CO/NO/NO_2 systems

Parameter	CO	NO	NO_2
Minimum range	0 to 250 ppm	0 to 30 ppm	0 to 2 ppm
Lower detectable limit	3 ppm	1 ppm	0,05 ppm
Expanded measurement uncertainty	3 ppm or 3 % of reading[a]	1 ppm	0,05 ppm or 5 % of reading[a]
Resolution	1 ppm	1 ppm	0,05 ppm
Response time: rise fall	 ≤ 120 s ≤ 120 s	 ≤ 120 s ≤ 120 s	 ≤ 120 s ≤ 120 s
Operating temperature	−20 to 50 °C	-20 to 50 °C	-20 to 50 °C

[a] Whichever is greater.

5.3.2 Reference barometer

A metrologically traceable reference barometer, with an uncertainty of 0,5 kPa U_{95}, is required for the calibration of any pressure transducers that form part of the measurement system, or to standardize flow through calibration cell conditions when performing checks or calibrations of the system.

Organizations performing the tests outlined in this clause shall meet the requirements of ISO/IEC 17025.

5.3.3 Reference thermometer

A metrologically traceable reference thermometer, with an uncertainty of 0,5 °C U_{95}, is required for the calibration of any temperature sensors that form part of the measurement system, or to standardize flow through calibration cell conditions when performing checks or calibrations of the system.

Organizations performing the tests outlined in this clause shall meet the requirements of ISO/IEC 17025.

5.3.4 Reference path length measurement device (for open path instruments only)

A metrologically traceable reference distance measuring device, with an uncertainty of 0,5 % U_{95}, is required to make an accurate determination of the measurement path length for open path instruments. The reference path length measurement device shall be checked over a path length of at least the instrument measurement path length.

Organizations performing the tests outlined in this clause shall meet the requirements of ISO/IEC 17025.

5.3.5 Reference flow through calibration cell length measurement device (for open path instruments only)

A metrologically traceable reference distance measuring device, with an uncertainty of 0,5 % U_{95}, is required to make an accurate determination of the length of the flow through calibration cell(s) for open path instruments. The reference path length measurement device shall be checked over a distance of at least the longest calibration cell path length.

Organizations performing the tests outlined in this clause shall meet the requirements of ISO/IEC 17025.

5.4 Procedure

5.4.1 Open path instruments

The procedure shall be as follows:

a) Ensure that the transceiver and retroreflector or transmitter and receiver units are installed such that the optical path is unimpeded by tunnel equipment or other obstructions, whilst allowing ease of access for instrument maintenance and calibration. Shorter optical paths will improve light levels however, they can result in higher detection limits and greater measurement uncertainty.

b) Ensure that the transceiver and retroreflector or transmitter and receiver units are firmly mounted on materials with low thermal expansion to minimize alteration of the light beam alignment due to temperature variations.

c) Ensure that instruments are not subject to excessive vibration and that the electricity supply is stable.

d) For equipment installed at the tunnel portals or entry/exit ramps, ensure that the optical path orientation is such that it avoids strong scattered radiation (e.g. sunlight) directly entering the transceiver or receiver unit.

e) Check the horizontal and vertical alignments of the units.

f) Accurately measure the distance between the transceiver and retroreflector or the transmitter and receiver using a reference path length measurement device (5.3.4).

g) Set up the instrument and carry out initial checks in accordance with the manufacturer's instructions (e.g. setting the path length, configuring and scaling of analogue outputs, setting of alarm values and level of damping) and the requirements of 5.5.

h) Take measurements in accordance with the manufacturer's instructions and ensure that the values obtained relate to the correct date and time.

NOTE Conducting the optical path alignment under low light or dark conditions can assist when adjusting the focus.

Where possible, optical path alignment and focusing should be performed under temperature conditions that approximate the mid-range of the expected minimum and maximum temperature range at the monitoring location.

During tunnel wall washing or deluge testing for the fire system, caps should be installed on the instrument dust protection tubes to prevent water ingress, where applicable.

5.4.2 Single point instruments

The procedure shall be as follows:

a) Install the equipment such that there is ease of access for instrument maintenance and calibration.

b) Ensure that instruments are not subject to sunlight, excessive vibration and that the electricity supply is stable.

c) Set up the instrument and carry out initial checks in accordance with the manufacturer's instructions (e.g. configuring and scaling of analogue outputs, setting of alarm values and level of damping) and the requirements of 5.5.

d) Take measurements in accordance with the manufacturer's instructions and ensure that the values obtained relate to the correct date and time.

During tunnel wall washing or deluge testing for the fire system, covers should be installed on the instruments to prevent water ingress, where applicable.

5.5 Instrument checks and calibrations

5.5.1 General

Calibration of an instrument establishes the quantitative relationship between the pollutant concentration input and the instrument's response. Only reference test atmospheres shall be used to adjust the instrument's output.

Instrument checks and calibrations shall be carried out in accordance with the frequencies specified by the equipment manufacturer and in accordance with Table 5.

In addition, instrument checks and calibrations shall be carried out:

a) prior to decommissioning or physical relocation of the instrument, if operational;

b) following physical relocation of the instrument;

c) after any repairs that might affect the instrument's response; and

d) upon any indication of an instrument malfunction or change in response that may cause the instrument to drift by more than the values given in Table 5.

NOTE Checks and calibrations specified in this clause can be omitted if the CO, NO or NO_2 measuring instrument provides proven equivalent self-test functions (e.g. read-back of analogue or digital outputs, zero and span checks).

5.5.2 Open path instruments

Open path instruments shall be calibrated as directed by the instrument's operation or instruction manual and in accordance with the general guidance provided here.

Based on the Beer-Lambert Law, absorption is dependent on both the gas concentration and the optical path length. Consequently, the light absorbed by the pollutant is a function of the total number of molecules of that gas between the transmitter and the receiver. Therefore, calibrations can theoretically be carried out at high concentrations over short distances or relatively low concentrations over longer distances, provided that the product of concentration times distance is constant.

Open path instrument checks and calibrations are generally carried out utilizing relatively high concentrations over short distances, due to increased uncertainty at lower gas concentrations. In addition, short calibration path lengths are easier to achieve in the field.

Instrument span checks and calibrations are conducted using a flow through calibration cell attached to the transceiver or receiver unit, with a reference test atmosphere introduced to the cell at a low flow rate.

By varying the number and length of flow through calibration cells through which the light beam travels, different gas concentrations can be simulated from the one reference test atmosphere. Alternatively, the concentration of the reference test atmosphere can be varied by using either multiple reference test atmospheres or dilution apparatus, with only one flow through calibration cell required.

The calculated gas concentration over the measurement path is as given in Formula (3):

$$c = \frac{c_r \times L_c}{L} + \frac{c_b \times (L - L_c)}{L} \quad (3)$$

where

c is the calculated gas concentration over the optical path length, in ppm;

c_r is the reference test atmosphere concentration, in ppm;

c_b is the background pollutant concentration, in ppm;

L_c is the calibration cell length, in m;

L is the measurement path length, in m.

Instrument checks and calibrations are normally conducted during tunnel closures, consequently the second term of the formula, which allows for the background pollutant concentration, is not normally significant at span gas concentrations. It may, however, become significant if there are idling vehicles or fuelled equipment operating nearby, when conducting measurements at the lower concentrations associated with a multipoint precision check or due to unusual environmental conditions such as fog. To reduce high background concentrations operation of the tunnel mechanical ventilation system may be necessary.

The background pollutant concentration is the average of the concentrations measured by the open-path instrument under test immediately before and after the period of calibration.

Open-path instruments should be tested during periods when pollutant concentrations and other optical interferences, such as fog, are relatively low and steady. Also, to avoid interference with the measurements, ensure that the outlet from the flow through calibration cell is directed away from the measurement path by attaching tubing to the cell exit port.

The response of open path instruments is a function of the total number of molecules in the light path, with some instruments correcting the response based on measured ambient temperature and pressure. For those instruments where this does not occur, the calculated concentration should be corrected based on the historical average temperature and pressure at the monitoring location for the proposed period between span calibrations, once the initial span check has been completed to confirm instrument performance for the preceding period:

$$c_s = c \times P_c/P_a \times T_a/T_c \quad (4)$$

where

c_s is the span gas concentration over the optical path length, in ppm;

P_a is the historical average ambient barometric pressure for the proposed period between calibrations, in kPa;

P_c is the barometric pressure at the time of calibration, in kPa;

T_a is the historical average ambient temperature for the proposed period between calibrations, in kelvins;

T_c is the temperature at the time of calibration, in kelvins.

Alternatively, the span concentration may be referenced to standard temperature and pressure (standard temperature and 101,3 kPa). If applicable, the method selected shall be stated in the test report.

Sealed cells containing a high concentration of the pollutant under measurement are available from some equipment manufacturers. Sealed cells can be used to check the performance of the instrument in the period between calibrations but shall not replace the instrument calibration requirements of this document.

5.5.3 Single point instruments

Single point instruments shall be calibrated as directed by the instrument's operation or instruction manual and in accordance with the general guidance provided here.

Instrument zero and span checks and calibrations shall be carried out at the monitoring location by allowing the instrument to sample reference test atmospheres containing known pollutant concentrations. During the check or calibration, the instrument shall sample the zero or span reference test atmosphere through all sample lines, filters, scrubbers, conditioners and other components associated with the measurement system during normal road tunnel air quality monitoring.

5.5.4 Measurement path length (for open path instruments only)

For open path instruments the measurement path length shall be determined upon installation (Table 5) using a reference measurement device as described in 5.3.4. The measurement path length is normally defined as the distance between the face of the transceiver or transmitter unit and the face of the retroreflector or receiver unit, however this should be confirmed with the manufacturer.

A check of the measurement path length shall also be conducted whenever an instrument is reinstalled following maintenance or repair.

5.5.5 Flow through calibration cell length (for open path instruments only)

The length of the flow through calibration cell(s) used for open path instrument checks and calibrations shall be determined before initial use (see Table 5) using a reference measurement device as described in 5.3.5. The cell length shall be determined as the distance between the inner surfaces of the optical glass on each side of the cell.

It may be preferable to determine the distance between the outer surfaces of the cell and subtract the thickness of glass at each end. This method shall be repeatable and take into account variables such as o-rings used to seal glass surfaces.

5.5.6 Temperature and pressure checks

If pollutant concentrations are required to be reported in units of milligrams per cubic metre (expressed at standard temperature and 101,3 kPa), the average temperature shall be measured.

Temperature sensors shall be checked at intervals not exceeding twelve months. If there is a difference of more than ± 1 °C between the sensor and reference thermometer, the sensor shall be calibrated. A reference thermometer that complies with the requirements of 5.3.3 shall be used. The manufacturer's instructions detailing the specific temperature sensor check and calibration procedure(s) shall be followed.

A check shall also be conducted whenever the temperature sensor is subject to maintenance or repair.

Changes in barometric pressure have a lesser effect, consequently continuous measurement, whilst recommended, is not a requirement of this document. When used, pressure transducers shall be checked at intervals not exceeding twelve months. If there is a difference of more than ± 1 kPa between the transducer and the reference barometer, the transducer shall be calibrated. A reference barometer that complies with the requirements of 5.3.2 shall be used. The manufacturer's instructions detailing the specific pressure sensor check and calibration procedure(s) shall be followed.

A check shall also be done whenever the pressure sensor is subject to maintenance or repair.

5.5.7 Zero air

Zero air shall be free from contaminants and interferents likely to cause a detectable response on the test instrument. The concentration of oxygen in the zero air shall be within ± 2 % *v*/*v* of the normal composition of air (20,9 % *v*/*v*).

5.5.8 Reference test atmosphere

Reference test atmospheres of gaseous target compounds shall be produced from certified reference materials in accordance with ISO 6145, using zero air as a diluent gas. Alternatively, certified reference materials can be supplied direct to the instrument without dilution, when appropriate concentrations of the target compound are available.

Organizations providing reference material certificates shall meet the requirements of ISO/IEC 17025 or be a National Metrology Institute (NMI) included in the Bureau International des Poids et Mesures (BIPM) key comparison database (KCDB).

5.5.9 Zero check

5.5.9.1 Open path instruments

If the open path instrument is capable of performing a zero check, follow the manufacturer's instructions. However, open path instrument zero checks are normally not possible in the field. Under these circumstances the 'zero' readings under no traffic conditions shall be recorded during instrument span checks (see 5.5.11.1). If the flow through calibration cell remains in the measurement path during the zero check, flush the cell with nitrogen or zero air.

Zero checks should be conducted under late night/early morning conditions when ambient pollutant concentrations are normally low. To reduce high background concentrations resulting from fuel combustion in maintenance vehicles and equipment, operation of the tunnel mechanical ventilation system may be necessary.

An alternate method for the zero check is to plot the instrument readings over an extended time period (≥ 1 month) to obtain an estimate of the instrument zero reading.

5.5.9.2 Single point instruments

The zero-check procedure for single point instruments shall be as follows:

a) Following installation, set up the instrument in accordance with the manufacturer's instructions.

b) Allow the instrument to operate for several hours (preferably overnight) prior to conducting the zero check, to ensure that its operation has stabilized.

c) Supply zero air to the instrument, ensuring that it passes through any conditioning equipment. After allowing sufficient time for the instrument response to stabilise, record the instrument reading.

d) Calculate the drift (d) as follows:

$$d = \frac{(c_r - c_e)}{c_{fs}} \times 100 \qquad (5)$$

where

c_r is the recorded value;

c_e is the expected value;

c_{fs} is the full scale value.

5.5.10 Zero calibration

If the instrument zero drift exceeds the value given in Table 5, or twelve months have passed since the previous calibration, whichever occurs first, adjust the instrument response if necessary and record the final instrument reading.

5.5.11 Span check

5.5.11.1 Open path instruments

The span check procedure for open path instruments shall be as follows:

a) Following installation, set up the instrument in accordance with the manufacturer's instructions.

b) Allow the instrument to operate for several hours (preferably overnight) prior to conducting the zero check, to ensure that its operation has stabilized. Select a full-scale value to cover the range of expected concentrations in the road tunnel.

c) Record the instrument zero reading.

d) For sealed cells, install the cell in the instrument.

e) For flow through calibration cells, install and flush with nitrogen or zero air and confirm the instrument zero reading. Connect the certified reference material cylinder or dilution apparatus to the flow through calibration cell and introduce a reference test atmosphere corresponding to 75 % to 90 % of the selected full-scale range of the instrument. The flowrate shall be such that there is no significant pressure increase in the cell (typically 1 Lpm or less).

f) After allowing sufficient time for the instrument response to stabilize, record the instrument reading.

g) Record a second instrument zero reading to ensure that there has been no significant change in background concentration.

h) Calculate the zero and span drifts using Formula (5).

i) Disconnect the reference test atmosphere supply and remove the flow through calibration cell.

5.5.11.2 Single point instruments

The span check procedure for single point instruments shall be as follows:

a) Following installation, set up the instrument in accordance with the manufacturer's instructions.

b) Allow the instrument to operate for several hours (preferably overnight) prior to conducting the span check, to ensure that its operation has stabilized. Select a full-scale value to cover the range of expected concentrations in the road tunnel.

c) Supply a reference test atmosphere at 75 % to 90 % of the selected full-scale range to the instrument ensuring that it passes through any conditioning equipment. After allowing sufficient time for the instrument response to stabilize, record the instrument reading.

d) Calculate the span drift using Formula (5).

5.5.12 Span calibration

If the instrument span drift exceeds the values given in Table 5, or twelve months have passed since the previous calibration, whichever occurs first, adjust the instrument response if necessary and record the final readings. Sealed cells shall not be used for instrument calibration. Recheck the instrument zero following any span adjustment in accordance with the procedure described in 5.5.9.1 (open path instruments) or 5.5.9.2 (single point instruments).

For instruments with individual zero and span controls for NO and NO_2, each shall be adjusted to give a readout equal to the respective reference test atmosphere concentration.

5.5.13 Multipoint precision check

A multipoint precision check shall only be performed immediately after a zero check/calibration and span calibration as described in 5.5.9 to 5.5.12. The procedure shall be as follows:

a) Upon commissioning or after any repairs that might affect the instrument's linearity, an extended multipoint precision check shall be performed. Supply to the instrument at least three non-zero reference test atmospheres approximately equally spaced over the measurement range (e.g. 25 %, 50 % and 75 %), or in the case of infra-red instruments six non-zero reference test atmospheres approximately equally spaced over the measurement range (e.g. 15 %, 30 %, 45 %, 60 %, 75 %, 90 %). After allowing sufficient time for the instrument response to stabilize, record the measured concentration for each reference test atmosphere and zero.

b) For subsequent multipoint precision checks, generate at least three non-zero reference test atmospheres, approximately equally spaced (e.g. 25 %, 50 %, 75 %) over the measurement range. After allowing sufficient time for the instrument response to stabilize, record the measured concentration for each reference test atmosphere and zero.

c) Calculate the standard error of the y estimate using the Formula (6):

$$S_{y,x} = \sqrt{\left[\frac{1}{n(n-2)}\right]\left[n\sum y^2 - \left(\sum y\right)^2 - \frac{\left[n\sum xy - \left(\sum x\right)\left(\sum y\right)\right]^2}{n\sum x^2 - \left(\sum x\right)^2}\right]} \qquad (6)$$

where

$S_{y,x}$ is the standard error of the y estimate;

y is the measured concentration;

x is the expected concentration;

n is the number of observations.

The standard error for the y estimate shall be less than 2 % of the full-scale value (see Table 5).

5.5.14 System component check

Cables, recorders, signal conditioning and data processing devices can corrupt the instrument's output.

A system component check shall be conducted on a 12-month basis to ensure the transmitted instrument output matches that received at the data recording device. For example, if the instrument gives a 20 mA output with a CO concentration of 250 ppm, then apply a 20 mA signal to the system to confirm that 250 ppm is indicated at the data recording device.

Check that the response is within the tolerance given in Table 5. If the result is not within the tolerance, identify and rectify the cause and repeat the procedure until the response is within the tolerance.

Table 5 — Instrument check and calibration requirements for tunnel CO/NO/NO_2 systems

Parameter	Criterion	Frequency
Zero check	± 2 % FS	≤ 3 months[b]
Span check	± 5 % FS	≤ 3 months[b]
Zero calibration	± 2 % FS	≤ 12 months
Span calibration	± 5 % FS	≤ 12 months
Multipoint precision check	2 % FS[a]	≤ 12 months
System component check	± 0,2 % FS	≤ 12 months
Measurement path length (open path only)	± 5 % FS	Initial[c]
Flow through calibration cell length (open path only)	± 5 % FS	Initial[c]
Measurement path temperature check (where applicable)	± 1 °C	≤ 12 months
Measurement path pressure check (where applicable)	± 1 kPa	≤ 12 months

[a] Allowable drift for a multipoint precision check is defined by the standard error of the y estimate (5.5.13).

[b] The period between zero checks and span checks may be extended to 6 months once sufficient data is available to confirm the stability of instrument response.

[c] Recalibration and path length measurement shall be undertaken following any maintenance or changes that may affect the measurement path or calibration cell length.

5.6 Maintenance

5.6.1 General

Maintenance should be carried out in accordance with the frequencies specified in Table 6. Manufacturers may require additional procedures.

A detailed log of all performance checks and maintenance undertaken shall be maintained and retained with the original CO, NO and NO_2 data.

The maintenance regime recommended in this clause is for preventive maintenance, with the maintenance components and frequencies recommended minimums. When the manufacturer makes claims regarding maintenance intervals that exceed these minimum requirements, they shall be deemed as acceptable if accompanied by a certificate issued from an organization other than the equipment manufacturer that meets the requirements of ISO/IEC 17025.

NOTE : Condition based maintenance or predictive maintenance can be used as alternative regimes, given that these systems determine differing maintenance components and frequencies.

5.6.2 Cleaning of optical interfaces

To maintain light levels, the optical interfaces on the open path instrument transmitter and receiver or transceiver and retroreflector should be cleaned every 6 months or more frequently when significant loss of sensitivity is observed.

5.6.3 Light source/electrochemical cell replacement

The light source or electrochemical cell should be replaced periodically, based on the manufacturer's recommendations.

5.6.4 Optical alignment

The open path instrument transmitter and receiver or transceiver and retroreflector may become misaligned over time, requiring periodic realignment. Significant loss of sensitivity may indicate that realignment is required, otherwise realignment should be performed at least every 6 months.

Table 6 — Routine maintenance for tunnel CO/NO/NO_2 systems

Maintenance component	Frequency
Cleaning of optical interfaces	≤ 6 months
Replacement of light source/electrochemical cell[a]	Manufacturer's instructions
Open path instrument optical alignment check	≤ 6 months
[a] The frequency of electrochemical cell replacement is dependent on the instrument and tunnel conditions, however, indicative replacement periods for CO and NO cells is 2 to 3 years and for NO_2 cells 3 to 12 months.	

5.7 Calculation and expression of results

Instruments normally provide a readout in ppm. Where concentrations are required to be expressed in mass per unit volume, readings shall be converted using Formula (7):

$$C_{\mathrm{m}} = \frac{C_v \times m}{V_{\mathrm{m}}} \tag{7}$$

where

C_{m} is the concentration of pollutant in milligrams per cubic metre (expressed at standard temperature and 101,3 kPa);

C_{v} is the concentration of pollutant in ppm;

m is the molecular weight of pollutant;

V_{m} is the molar volume (e.g. 22,4 l per gram mole at 0 °C and 101,3 kPa).

Some instruments may perform this conversion automatically. Ensure that the standard conditions employed by the instrument when making this conversion are correct.

5.8 Measurement uncertainty

The measurement uncertainty of this method will vary for each specific application. Factors affecting the overall uncertainty include (but are not limited to) uncertainties associated with the reference test atmosphere concentration, flow through calibration cell and measurement path lengths, allowable span and zero drifts, measurement path temperature and pressure corrections, calibration devices and recording instrumentation, and will vary from site to site. As a guide, uncertainties of 10 % of reading can be achieved using this method, however, the measurement uncertainty shall be determined based on individual laboratory practices.

NOTE A suitable method for calculating measurement uncertainty can be found in ISO/IEC Guide 98-3.

6 Testing parameter — visibility

6.1 General

Clause 6 describes continuous, direct-reading instruments for determining visibility in road tunnels. Providing the instrument performance is within the specifications given in Table 7, alternate methods may be used within the context of this document.

6.2 Principle

Objects become visible to an observer when light from the object is detected by the observer. A particular object is seen against its surroundings by virtue of the difference in either intensity or wavelength of the radiation emanating from it compared with that emanating from its surroundings.

Light is attenuated through scattering and absorption by both gases and particles in the atmosphere, with the result that objects viewed at a distance become less visible than when viewed up close. A dark object appears lighter with increasing distance and a light-coloured object appears darker. In either case a loss of contrast occurs between the object and its surroundings until at a sufficiently large distance the object merges into the background.

Visibility degradation in road tunnels is principally due to the light scattering properties of fine particles less than 2,5 µm in diameter, with the most efficient light scattering particles within the size range corresponding to the wavelength of visible light, 0,4 µm to 0,7 µm.

In road tunnels visibility is measured using open path transmissometers or single point light scattering instruments, installed at various locations along the tunnel length.

The instruments calculate the extinction coefficient (K), the reciprocal of the distance in metres over which 63 % of initial light intensity is lost by particle scattering. The extinction coefficient is dependent on particle concentration, light distribution and wavelength (λ) of the incident light. Scattering is proportional to $\lambda^{-\alpha}$ where α is typically 0,5 to 2,5 for particles, depending on the size distribution, with α increasing as the mass mean diameter of the fine particles decreases.

Attenuation of light passing through the atmosphere may be represented in this instance by the Beer-Lambert law given in Formula (8):

$$I = I_o e^{-KL} \tag{8}$$

where

I is the intensity of light at the observer;

I_o is the initial light intensity;

L is the path length of light (i.e. the object to observer distance);

K is the extinction coefficient (due to absorption and scattering);

$= K_{ag} + K_{sg} + K_{ap} + K_{sp}$ where K is the extinction coefficient and the subscripts, a, s, g and p refer to absorption, scattering, gases and particles respectively.

In polluted atmospheres, such as in road tunnels, the loss of light intensity by particle scattering is the major cause of light extinction. Consequently, terms other than K_{sp} are neglected.

Transmissometers measure the proportion of light transmitted (I/I_o) through the road tunnel atmosphere over a known distance between a light source of known intensity (transmitter) and a light measurement device (receiver). Alternatively, an autocollimator or retroreflector may be used with a transmitter/receiver (transceiver) to double the measurement path length.

For transmissometers the relationship between K and light transmission is logarithmic and is given in Formula (9):

$$K = -\ln(I/I_0)/L \quad (9)$$

Scattered light instruments measure the amount of forward scattered light, at a specified angle to the incident light, using a photodetector. Over the range of particulate matter concentrations and size distributions normally experienced in road tunnels, the photodetector has an approximate linear response to the extinction coefficient, K, however, the instrument response can be affected by changes in particulate matter chemical composition and colour, in addition to particle size distribution.

In scattered light instruments the scattering coefficient β is determined by measuring the amount of forward scattered light flux Φ_s, at a specific angle θ to the incident light, using a photodetector with area S as given in Formula (10):

$$\Phi_s = \int_S I_{s,\Omega}(\theta)\, d\Omega \quad (10)$$

Here, $I_{s,\Omega}(\theta)$ is the radiant flux that is scattered by the atmosphere within a distance Δx. Δx is the short section of the incident light path over which incident light scatters towards the photodetector. With the flux Φ of the incident light beam, Formula (11) relates the scattered light flux to β:

$$\beta \cdot \Delta x = \frac{2\pi \cdot \int_0^{\pi} I_{s,\Omega}(\theta) \cdot \sin(\theta)\, d\theta}{\Phi} \quad (11)$$

By using a modulated light source or by shielding the measurement from other light sources, light scattering instruments can be used in daylight or at night.

Scattered light instruments rely on diffusion through a grill or are mechanically or thermally aspirated. Compared to transmissometers, they are smaller in size, do not require optical alignment and are less prone to soiling.

Instrument options include heaters to eliminate the effect of fog with the objective of eliminating the risk of fog accumulation inside the tunnel through tunnel ventilation. Fog elimination is considered important for visibility instruments located near tunnel portals, however, it should also be recognised that the use of heaters can result in underestimation of the extinction coefficient within the tunnel.

6.3 Apparatus

6.3.1 Instrument

The instrument is a continuous direct-reading instrument that meets or exceeds the performance specifications given in Table 7.

The instrument may be used over any range within the limits of this document, provided it has been calibrated in accordance with 6.5.

The manufacturer's published performance specifications shall be deemed as acceptable evidence of conformance to the given requirements, if accompanied by a statement of measurement uncertainty, issued by an organization that meets the requirements of ISO/IEC 17025.

Table 7 — Instrument performance specifications for tunnel visibility systems

Parameter	Requirement
Range	0 to 0,015 m^{-1}
Wavelength[a]	500 to 700 nm
Expanded measurement uncertainty	0,001 m^{-1}
Resolution	0,0001 m^{-1}
Response time: rise fall	 ≤ 60 s ≤ 60 s
Operating temperature	−20 to 50 °C

[a] Either the light source of the instrument is within this range or the instrument has to be calibrated to correspond with measured K values in this wavelength range.

6.3.2 Reference path length measurement device

A metrologically traceable reference distance measuring device with a measurement uncertainty of 0,5 % U_{95} is required to make an accurate determination of the measurement path length. The device shall be checked over a path length of at least the instrument measurement path length.

Organizations performing the tests outlined in this clause shall meet the requirements of ISO/IEC 17025.

6.4 Procedure

6.4.1 Transmissometer

The procedure shall be as follows:

a) Ensure that the transmissometer is installed such that the optical path is unimpeded by tunnel equipment or other obstructions, whilst allowing ease of access for instrument maintenance and calibration. Shorter optical paths will improve light levels however, they can result in higher detection limits and greater measurement uncertainty.

b) The transmissometer shall be firmly mounted on materials with low thermal expansion to minimize alteration of the light beam alignment due to ambient temperature variations.

c) Ensure that the transmissometer is not subject to excessive vibration and that the electricity supply is stable.

d) For equipment installed at the tunnel portals or entry/exit ramps, ensure that the optical path orientation is such that it avoids strong scattered radiation (e.g. sunlight) directly entering the transceiver or receiver unit.

e) Check the horizontal and vertical alignments of the units.

f) Accurately measure the distance between the transceiver and retroreflector or the transmitter and receiver using a reference measurement device as described in 6.3.2. The measurement path length is normally defined as the distance between the face of the transceiver or transmitter unit and the face of the retroreflector or receiver unit, however, this should be confirmed with the manufacturer. A check of the measurement path length shall also be conducted whenever an instrument is reinstalled following maintenance or repair (see Table 8).

g) Set up the instrument and carry out initial checks in accordance with the manufacturer's instructions (e.g. configuring and scaling of analogue outputs, setting of alarm values and level of damping) and the requirements of 6.5.

h) Take measurements in accordance with the manufacturer's instructions and ensure that the values obtained relate to the correct date and time.

NOTE Conducting the optical path alignment under low light or dark conditions can assist when adjusting the focus.

Where possible, optical path alignment and focusing should be performed under temperature conditions that approximate the mid-range of the expected minimum and maximum temperature range at the monitoring location.

During tunnel wall washing or deluge testing for the fire system, caps should be installed on the instrument dust protection tubes to prevent water ingress, where applicable.

6.4.2 Scattered light instrument

The procedure shall be as follows:

a) Ensure that the instrument is not subject to excessive vibration and that the electricity supply is stable.

b) For instruments installed at the tunnel portals or entry/exit ramps, ensure that strong scattered radiation (e.g. sunlight) cannot affect the instrument response.

c) Set up the instrument and carry out initial checks in accordance with the manufacturer's instructions (e.g. configuring and scaling of analogue outputs, setting of alarm values and level of damping) and the requirements of 6.5.

d) Take measurements in accordance with the manufacturer's instructions and ensure that the values obtained relate to the correct date and time.

During tunnel wall washing or deluge testing for the fire system, covers should be installed on the instruments to prevent water ingress, where applicable.

6.5 Instrument checks and calibrations

6.5.1 General

Calibration of an instrument establishes the quantitative relationship between visibility and the instrument's response.

Instrument checks and calibrations shall be carried out in accordance with the frequencies specified by the equipment manufacturer and in accordance with Table 8.

In addition, instrument checks and calibrations shall be carried out:

a) prior to decommissioning or physical relocation of the instrument, if operational;

b) following physical relocation;

c) after any repairs that might affect the instrument's response; and

d) upon any indication of an instrument malfunction or change in response that may cause the instrument to drift by more than the values given in Table 8.

Instrument calibration is conducted using a certified reference material (e.g. test cell(s) or neutral density filter(s)) attached to the scattered light instrument or transmissometer transceiver or receiver unit, with the cell or filter providing a rated value for the measured extinction coefficient.

Calibrations are normally conducted during tunnel closures, with the background extinction coefficient assumed to be low. However, this may not be the case if there are idling vehicles or fuelled equipment

