UNITED
NATIONS

# Worldwide Harmonised Heavy Duty Emissions Certification Procedure

# [DRAFT GLOBAL TECHNICAL REGULATION (GTR)]

## UN/ECE-WP 29 - GRPE
## WHDC Working Group

**Whilst this document is presented in the format of a draft GTR as defined by WP.29 / 883, the WHDC informal group / GRPE recognise that the issue of GTR's and specific performance requirements / limit values is still being considered. Accordingly, GRPE will finalise the document once WP.29 / AC.3 has reached a decision.**

**This document covers the general technical contents of the GTR procedure, as approved by the 47th GRPE on 15.01.2004. Chapters in square brackets will have to be completed later. For finalization of the technical details, it is proposed to establish a WHDC Drafting Committee.**

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**ECONOMIC COMMISSION FOR EUROPE**

INLAND TRANSPORT COMMITTEE

World Forum for Harmonisation of Vehicle Regulations (WP.29)

DRAFT GLOBAL TECHNICAL REGULATION (GTR)

UNIFORM PROVISIONS CONCERNING THE TEST PROCEDURE FOR COMPRESSION-IGNITION (C.I.) AND NATURAL GAS (NG) ENGINES AS WELL AS POSITIVE-IGNITION (P.I) ENGINES FUELLED WITH LIQUEFIED PETROLEUM GAS (LPG) AND VEHICLES EQUIPPED WITH C.I. AND NG ENGINES AND P.I. ENGINES FUELLED WITH LPG, WITH REGARD TO THE EMISSIONS OF  POLLUTANTS BY THE ENGINE

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# A. **Statement of Technical Rationale and Justification**

## 1. Technical and Economic Feasibility

The objective of this proposal is to establish a harmonised Global Technical Regulation (GTR) covering the type-approval procedure for heavy-duty engine exhaust emissions. The basis will be the test procedure developed by the WHDC informal group of GRPE (see final summary, [informal document no. 4] to the 46th GRPE).

Regulations governing the exhaust emissions from heavy-duty engines have been in existence for many years but the test cycles and methods of emissions measurement vary significantly. To be able to correctly determine the impact of a heavy-duty vehicle on the environment in terms of its exhaust pollutant emissions, a laboratory test procedure, and consequently the GTR, needs to be adequately representative of real-world vehicle operation.

The proposed regulation is based on new research into the world-wide pattern of real heavy commercial vehicle use. From the collected data, two representative test cycles, one transient test cycle (WHTC) and one steady state test cycle (WHSC), have been created covering typical driving conditions in the European Union, the United States of America and Japan. Alternative emission measurement procedures have been developed by an expert committee in ISO and have been published in ISO 16183. This standard reflects the state-of-the-art in exhaust emissions measurement technology with the potential for accurately measuring the pollutant emissions from future low emission engines.

The WHTC and WHSC test procedures reflect world-wide on-road heavy-duty engine operation as closely as possible and provide a marked improvement in the realism of the test procedure for measuring the emission performance of existing and future heavy-duty engines.

The performance levels (emissions test results) to be achieved in the GTR will be discussed on the basis of the most recently agreed legislation in the Contracting Parties, required by the 1998 Agreement. On the basis of heavy-duty engine emission measurements according to the procedures contained within this GTR, it will be possible to propose pollutant emission limit values that are compatible to existing or future limit values in different regions/countries.

## 2. Anticipated benefits

Compared to the measurement methods defined in existing legislation in Contracting Parties, the testing methods defined in this GTR are much more representative of in-use driving behaviour of commercial vehicles world-wide.

As a consequence, it can be expected that the application of this GTR for emissions legislation within the Contracting Parties will result in a higher control of in-use emissions due to the improved correlation of the test methods with in-use driving behaviour.

Additionally, heavy commercial vehicles and their engines are increasingly produced for the world market. It is economically inefficient for manufacturers to have to prepare substantially different models in order to meet different emission regulations and methods of measuring emissions, which, in principle, aim at achieving the same objective. To enable manufacturers to develop new models more effectively and within shorter time it is desirable that a GTR should be developed.

## 3. [Potential cost effectiveness]

Reserved. Not yet clear whether this chapter is requested or not.

B. **Text of Regulation**

# 1 Scope and Purpose

This regulation aims at providing a world-wide harmonised method for the determination of the levels of pollutant emissions from heavy-duty engine used in commercial vehicles in a manner which is representative of real world vehicle operation. The results can be the basis for the regulation of pollutant emissions indicated by the manufacturer within regional type-approval and certification procedures.

# 2 Application

This Regulation applies to the emission of gaseous and particulate pollutants from compression-ignition engines, natural gas engines and positive-ignition engines fuelled with LPG, used for propelling motor vehicles having a design speed exceeding 25 km/h and having a total mass exceeding 3.5 tonnes.

# 3 Definitions, Symbols and Abbreviations

## 3.1 Definitions

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

Other definitions from ECE R49 will be added later.

**particulate matter:** Any material collected on a specified filter medium after diluting exhaust with clean filtered air to a temperature of less than or equal to 325 K (52°C), as measured at a point immediately upstream of the filter; this is primarily carbon, condensed hydrocarbons, and sulfates with associated water

**gaseous pollutants:** Carbon monoxide, hydrocarbons and/or non-methane hydrocarbons, oxides of nitrogen (expressed in nitrogen dioxide ($NO_2$) equivalent), formaldehyde, and methanol

**partial flow dilution method:** Process of separating a part of the raw exhaust from the total exhaust flow, then mixing it with an appropriate amount of dilution air prior to the particulate sampling filter

**full flow dilution method:** Process of mixing dilution air with the total exhaust flow prior to separating a fraction of the diluted exhaust stream for analysis

**specific emissions:** Mass emissions expressed in g/kWh

**steady-state test cycle:** Test cycle with a sequence of engine test modes in which the engine is given sufficient time to achieve defined speed, torque, and stability criteria at each mode

**transient test cycle:** Test cycle with a sequence of normalized speed and torque values that vary relatively quickly with time

**response time:** Difference in time between a rapid change of the component to be measured at the reference point and the appropriate change in the response of the measuring system whereby the change of the measured component is at least 60% FS and takes place in less than 0,1 second

NOTE The system response time ($t_{90}$) consists of the delay time to the system and of the rise time of the system. The response time may vary dependent on where the reference point for the change of the component to be measured is defined, either at the sampling probe or directly at the port entrance of the analyzer; in this International Standard, the sampling probe is defined as the reference point.

**delay time:** Time between the change of the component to be measured at the reference point and a system response of 10% of the final reading ($t_{10}$)

NOTE For the gaseous components, this is basically the transport time of the measured component from the sampling probe to the detector. For the delay time, the sampling probe is defined as the reference point.

**rise time:** Time between the 10% and 90% response of the final reading ($t_{90} - t_{10}$)

NOTE This is the instrument response after the component to be measured has reached the instrument. For the rise time, the sampling probe is defined as the reference point.

**transformation time:** Time between the change of the component to be measured at the reference point and a system response of 50% of the final reading ($t_{50}$)

NOTE For the transformation time, the sampling probe is defined as the reference point. The transformation time is used for the signal alignment of different measurement instruments.
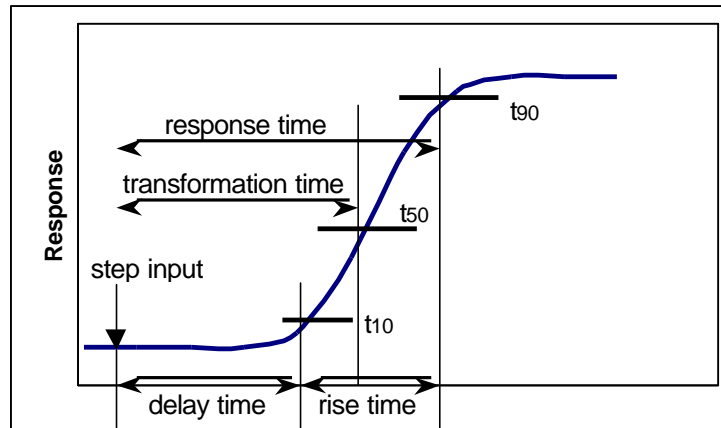


**Figure 1 — Definitions of system response**

## 3.2 General symbols

| Symbol | Unit | Term |
|---|---|---|
| $A/F_{st}$ | - | Stoichiometric air to fuel ratio |
| $c$ | ppm / Vol% | Concentration |
| $C_c$ | - | Slip Factor |
| $d_e$ | m | Exhaust pipe diameter |
| $d_p$ | m | Sampling probe diameter |
| $d_{PM}$ | m | Particle diameter |
| $f$ | Hz | Data sampling rate |
| $f_a$ | - | Laboratory atmospheric factor |
| $E_{CO2}$ | % | $CO_2$ quench of $NO_x$ analyzer |
| $E_E$ | % | Ethane efficiency |
| $E_{H2O}$ | % | Water quench of $NO_x$ analyzer |
| $E_M$ | % | Methane efficiency |
| $E_{NOx}$ | % | Efficiency of $NO_x$ converter |
| $h$ | Pa*s | Dynamic viscosity of exhaust gas |
| | | |
| | | |

| Symbol | Unit | Term |
|--------|------|------|
| $H_a$ | g/kg | Absolute humidity of the intake air |
| $i$ | - | Subscript denoting an instantaneous measurement (e.g.1 Hz) |
| $k_f$ | - | Fuel specific factor |
| $k_{h,D}$ | - | Humidity correction factor for $NO_x$ for CI engines |
| $k_{h,G}$ | - | Humidity correction factor for $NO_x$ for SI engines |
| $k_w$ | - | Dry to wet correction factor for the raw exhaust gas |
| $l$ | - | Excess air ratio |
| $m_{edf}$ | kg | Mass of equivalent diluted exhaust gas over the cycle |
| $m_f$ | mg | Particulate sample mass collected |
| $m_{gas}$ | g | Mass of gaseous emissions (over the test cycle) |
| $m_{PM}$ | g | Mass of particulate emissions (over the test cycle) |
| $m_{se}$ | kg | Exhaust sample mass over the cycle |
| $m_{sed}$ | kg | Mass of diluted exhaust gas passing the dilution tunnel |
| $m_{sep}$ | kg | Mass of diluted exhaust gas passing the particulate collection filters |
| $M_{gas}$ | g/kWh | Specific emission of gaseous emissions |
| $M_{PM}$ | g/kWh | Specific emission of particulate emissions |
| $n$ | - | Number of measurements |
| $p_a$ | kPa | Saturation vapor pressure of the engine intake air |
| $p_b$ | kPa | Total atmospheric pressure |
| $p_r$ | kPa | Water vapor pressure after cooling bath |
| $p_s$ | kPa | Dry atmospheric pressure |
| $P$ | - | Particle penetration |
| $q_{mad}$ | kg/s | Intake air mass flow rate on dry basis |
| $q_{maw}$ | kg/s | Intake air mass flow rate on wet basis |
| $q_{mCe}$ | kg/s | Carbon mass flow rate in the raw exhaust gas |
| $q_{mCf}$ | kg/s | Carbon mass flow rate into the engine |
| $q_{mCp}$ | kg/s | Carbon mass flow rate in the partial flow dilution system |
| $q_{mdew}$ | kg/s | Diluted exhaust gas mass flow rate on wet basis |
| $q_{mdw}$ | kg/s | Dilution air mass flow rate on wet basis |
| $q_{medf}$ | kg/s | Equivalent diluted exhaust gas mass flow rate on wet basis |

| Symbol | Unit | Term |
|--------|------|------|
| $q_{m\text{ew}}$ | kg/s | Exhaust gas mass flow rate on wet basis |
| $q_{m\text{ex}}$ | kg/s | Sample mass flow rate extracted from dilution tunnel |
| $q_{m\text{f}}$ | kg/s | Fuel mass flow rate |
| $q_{m\text{p}}$ | kg/s | Sample flow of exhaust gas into partial flow dilution system |
| $q_{v\text{s}}$ | l/min | System flow rate of exhaust analyzer system |
| $q_{v\text{t}}$ | cm³/min | Tracer gas flow rate |
| $r_{\text{d}}$ | - | Dilution ratio |
| $r_{\text{h}}$ | - | Hydrocarbon response factor of the FID |
| $r_{\text{m}}$ | - | Methanol response factor of the FID |
| $r_{\text{s}}$ | - | Average sample ratio |
| $\boldsymbol{r}$ | kg/m³ | Density |
| $\boldsymbol{r}_{\text{e}}$ | kg/m³ | Exhaust gas density |
| $\boldsymbol{r}_{\text{PM}}$ | kg/m³ | Particle density |
| $\boldsymbol{s}$ | | Standard deviation |
| $T$ | K | Absolute temperature |
| $T_{\text{a}}$ | K | Absolute temperature of the intake air |
| $t_{10}$ | s | Time between step input and 10% of final reading |
| $t_{50}$ | s | Time between step input and 50% of final reading |
| $t_{90}$ | s | Time between step input and 90% of final reading |
| $\boldsymbol{t}$ | s | Particle relaxation time |
| $u$ | - | Ratio between densities of gas component and exhaust gas |
| $V_{\text{s}}$ | l | Total volume of exhaust analyzer system |
| $W_{\text{act}}$ | kWh | Actual cycle work of the respective test cycle |
| $\boldsymbol{u}_{\text{e}}$ | m/s | Gas velocity in the exhaust pipe |
| $\boldsymbol{u}_{\text{p}}$ | m/s | Gas velocity in the sampling probe |

## 3.3   Symbols and abbreviations for the fuel composition

| | |
|--|--|
| $w_{\text{ALF}}$ | hydrogen content of fuel, % mass |
| $w_{\text{BET}}$ | carbon content of fuel, % mass |
| $w_{\text{GAM}}$ | sulfur content of fuel, % mass |
| $w_{\text{DEL}}$ | nitrogen content of fuel, % mass |
| $w_{\text{EPS}}$ | oxygen content of fuel, % mass |
| $\boldsymbol{a}$ | molar hydrogen ratio (H/C) |
| $\boldsymbol{b}$ | molar carbon ratio (C/C) |

$g$             molar sulfur ratio (S/C)

$d$             molar nitrogen ratio (N/C)

$e$             molar oxygen ratio (O/C)

referring to a fuel $C_b H_a O_e N_d S_g$

## 3.4   Symbols and abbreviations for the chemical components

| | |
|---|---|
| ACN | Acetonitrile |
| C1 | Carbon 1 equivalent hydrocarbon |
| $CH_4$ | Methane |
| $CH_3OH$ | Methanol |
| $C_2H_6$ | Ethane |
| $C_3H_8$ | Propane |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| DNPH | Dinitrophenyl hydrazine |
| DOP | Di-octylphtalate |
| HC | Hydrocarbons |
| HCHO | Formaldehyde |
| $H_2O$ | Water |
| NMHC | Non-methane hydrocarbons |
| $NO_x$ | Oxides of nitrogen |
| NO | Nitric oxide |
| $NO_2$ | Nitrogen dioxide |
| PM | Particulate matter |
| RME | Rapeseed oil methylester |

## 3.5   Abbreviations

| | |
|---|---|
| CLD | Chemiluminescent Detector |
| FID | Flame Ionization Detector |
| FTIR | Fourier Transform Infrared (Analyzer) |
| GC | Gas Chromatograph |
| HCLD | Heated Chemiluminescent Detector |
| HFID | Heated Flame Ionization Detector |
| HPLC | High Pressure Liquid Chromatograph |
| MW | Molecular Weight |
| NDIR | Non-Dispersive Infrared (Analyzer) |
| NMC | Non-Methane Cutter |
| % FS | Percent of full scale |

| SIMS | Soft Ionization Mass Spectrometer |
| Stk | Stokes number |

# 4  General Requirements

The components liable to affect the emission of gaseous and particulate pollutants shall be so designed, constructed and assembled as to enable the vehicle in normal use, despite the vibration to which it may be subjected, to comply with the provisions of this Regulation.

# 5  [Performance Requirements]

Reserved. Decision of AC.3 required.

## 5.1  [Application for approval]

## 5.2  [Approval]

## 5.3  Emission of gaseous and particulate pollutants

The emissions shall be determined on the WHTC and WHSC tests. The WHTC and WHSC test procedures are described in paragraph 7.

The emissions of gaseous and particulate pollutants and smoke by the engine submitted for testing shall be measured by the methods described in paragraph 7. Paragraph 9 describes the recommended analytical systems for the gaseous pollutants and the recommended particulate sampling systems.

Other systems or analyzers may be approved by the Technical Service if it is found that they yield equivalent results according to the statistical approach of paragraph 5.3.1.

### 5.3.1  Equivalency

The determination of system equivalency shall be based on a 7 sample pair (or larger) correlation study between the system under consideration and one of the systems of this Regulation. "Results" refer to the specific cycle weighted emissions value. The correlation testing is to be performed at the same laboratory, test cell, and on the same engine, and is preferred to be run concurrently. The test cycle to be used shall be the appropriate cycle the engine will be run on. The equivalency of the sample pair averages shall be determined by t-test statistics as described in Annex 10.4 obtained under the laboratory cell and the engine conditions described above. Outliers shall be determined in accordance with ISO 5725 and excluded from the database. The systems to be used for correlation testing shall be declared prior to the test and shall be approved by the Technical Service.

For introduction of a new system into the Global Technical Regulation the determination of equivalency shall be based upon the calculation of repeatability and reproducibility, as described in ISO 5725.

## 5.4  [Limit values]

## 5.5  Engine family

### 5.5.1  General

An engine family is characterized by design parameters. These shall be common to all engines within the family. In some cases there may be interaction of parameters. The engine manufacturer may decide, which engines belong to an engine family, as long as the membership criteria listed in 5.5.3 are respected.

### 5.5.2 Special cases

In some cases there may be interaction between parameters. This shall be taken into consideration to ensure that only engines with similar exhaust emission characteristics are included within in the same engine family. These cases shall be identified by the manufacturer and notified to the type approval authority. E.g., the number of cylinders may become a significant parameter on certain engines due to the fuel supply or air intake system, while with other designs the exhaust emissions characteristics are independent of the number of cylinders or their configuration.

In case of devices or features, which are not listed in 5.5.3 and which may have a strong influence on the level of emissions, this equipment shall be identified by the manufacturer on the basis of good engineering practice, and shall be notified to the type approval authority. It shall then be taken into account as a criterion for belonging to an engine family.

In addition to the parameters listed in 5.5.3, the manufacturer may introduce additional criteria allowing the definition of families of more restricted size. These parameters are not necessarily parameters that have an influence on the level of emissions.

### 5.5.3 Parameters Defining the Engine Family

**5.5.3.1 Combustion cycle**

- 2 stroke cycle

- 4 stroke cycle

- Rotary engine

- Others

**5.5.3.2 Configuration of the cylinders**

**5.5.3.2.1 Position of the cylinders in the block**

- V

- In line

- Radial

- Others (F, W, etc.)

**5.5.3.2.2 Relative position of the cylinders**

Engines with the same block may belong to the same family as lond as their bore center-to-center dimensions are the same.

**5.5.3.3 Main cooling medium**

- air

- water

- oil

**5.5.3.4 Individual cylinder displacement**

**5.5.3.4.1 Engine with a unit cylinder displacement ³ 0,75 dm³**

In order for engines with a unit cylinder displacement of $\geq$ 0,75 dm³ to be considered to belong to the same engine family, the spread of their individual cylinder displacements shall not exceed 15 % of the largest individual cylinder displacement within the family.

**5.5.3.4.2 Engine with a unit cylinder displacement < 0,75 dm³**

In order for engines with a unit cylinder displacement of < 0,75 dm³ to be considered to belong to the same engine family, the spread of their individual cylinder displacements shall not exceed 30 % of the largest individual cylinder displacement within the family.

**5.5.3.4.3 Engine with other unit cylinder displacement limits**

Engines with an individual cylinder displacement that exceeds the limits defined in 5.5.3.4.1 and 5.5.3.4.2 may be considered to belong to that family with the agreement of the parties involved. This agreement should be based on technical elements (calculations, simulations, experimental results etc.) showing that this excess

does not have a significant influence on the exhaust emissions.

**5.5.3.5    Method of air aspiration**

- naturally aspirated
- pressure charged
- pressure charged with charge cooler

**5.5.3.6    Fuel type**

- Diesel
- Petrol
- Gaseous fuel
    - Natural gas (NG)
    - Liquefied petroleum gas (LPG)
    - Hydrogen
    - Dimethylether (DME)
    - Others
- Alcohols
- Other fuels

NOTE      If the engine is designed for a given fuel, but used without basic design modifications with another fuel, the necessity for two different families should be based on technical elements. E.g., it is possible to consider a gas engine fueled with gasoline during warm-up as belonging to the same family as a pure gas engine.

**5.5.3.7    Combustion chamber type**

- Open chamber
- Divided chamber
- Other types

**5.5.3.8    Ignition Type**

- Spark ignition
- Compression ignition

**5.5.3.9    Valves and porting**

- Configuration
- Number of valves per cylinder

**5.5.3.10    Fuel supply type**

- Liquid fuel supply type
    - Pump and (high pressure) line and injector
    - In-line or distributor pump
    - Unit pump or unit injector
    - Common rail
    - Carburettor(s)
    - Others
- Gas fuel supply type
    - Gaseous
    - Liquid
    - Mixing units
    - Others

- Other types

**5.5.3.11      Miscellaneous devices**

- Exhaust gas recirculation (EGR)

- Water injection

- Air injection

- Others

NOTE      The influence of the listed devices on exhaust emissions depends largely on the specific layout and adapted control strategy. The decision as to whether an engine with these devices ca be considered as a part of the family shall be left to the manufacturer, provided he can give the technical elements for the decision (e.g. calculation, simulations, experimental results).

**5.5.3.12      Electronic control strategy**

The presence or absence of an electronic control unit (ECU) on the engine is regarded as a basic parameter of the family.

In the case of electronically controlled engines, the manufacturer shall presentthe technical elements explaining the grouping of these engines in the same family, i.e. the reasons why these engine can be expected to satisfy the same emission requirements.

These elements can be calculations, simulations, estimations, description of injection parameters, experimental results, etc.

Examples of controlled features are:

- Timing

- Injection pressure

- Multiple injection

- Boost pressure

- VGT

- EGR

**5.5.3.13      Aftertreatment systems**

The function and combination of the following devices are regarded as membership criteria for an engine family:

- Oxidation catalyst

- Three-way catalyst

- DeNOx system with selective reduction of NOx (addition of reducing agent)

- Other DeNOx systems

- Particulate trap with passive regeneration

- Particulate trap with active regeneration

- Other particulate traps

- Other devices

When an engine has been certified without aftertreatment system, whether as parent engine or as member of the family, then this engine, when equipped with a non-controlled aftertreatment system, may be included in the same engine family, if it does not require different fuel characteristics (e.g. most of the oxidation catalysts).

If it requires specific fuel characteristics (e.g. particulate traps requiring special additives in the fuel to ensure the regeneration process), the decision to include it in the same family shall be based on technical elements provided by the manufacturer. These elements should indicate that the expected emission level of the equipped engine satisfies the same limit value as the non-equipped engine.

When an engine has been certified with aftertreatment system, whether as parent engine or as member of a family, whose parent engine is equipped with the same aftertreatment system, then this engine, when equipped without aftertreatment system, must not be added to the same engine family.

### 5.5.4 Choice of the parent engine

#### 5.5.4.1 Compression ignition engines

The parent engine of the family shall be selected using the primary criterion of the highest fuel delivery per stroke at the declared maximum torque speed. In the event that two or more engines share this primary criterion, the parent engine shall be selected using the secondary criterion of highest fuel delivery per stroke at rated speed.

#### 5.5.4.2 Spark ignition engines

The parent engine of the family shall be selected using the primary criterion of the largest displacement. In the event that two or more engines share this primary criterion, the parent engine shall be selected using the secondary criterion in the following order of priority:

a)        the highest fuel delivery per stroke at the speed of declared rated power

b)        the most advanced spark timing

c)        the lowest EGR rate

#### 5.5.4.3 Remarks on the choice of the parent engine

Under certain circumstances, the approval authority may conclude that the worst case emission rate of the family can best be characterized by testing a second engine. Thus, the approval authority may select an additional engine for test based upon features which indicate that it may have the highest emission level of the engines within that family. In this case, the parties involved shall have the appropriate information to determine the engine within the family likely to have the highest emissions level. This engine may be directly selected for testing without any prior test of any engine selected according to 5.5.4.1 or 5.5.4.2.

If engines within the family incorporate other variable features which may be considered to affect exhaust emissions, these features shall also be identified and taken into account in the selection of the parent engine.

If engines within the family meet the same emission values over different useful life periods, this shall be taken into account in the selction of the parent engine.

## 5.6    [Production conformity]

# 6  Test Conditions

## 6.1    Engine Test Conditions

### 6.1.1    Test condition parameter

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

a) for compression-ignition engines:

Naturally aspirated and mechanically supercharged engines:

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

Turbocharged engines with or without cooling of the intake air:

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

 b) for spark ignition engines:

$$f_a = \left(\frac{99}{p_s}\right)^{1,2} \times \left(\frac{T_a}{298}\right)^{0,6}$$

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### 6.1.2 Test validity

For a test to be recognized as valid, the parameter $f_a$ shall be such that: $0,93 \le f_a \le 1,07$

## 6.2 Engines with charge air cooling

The charge air temperature shall be recorded and shall be, at the speed of the declared maximum power and full load, within $\pm$ 5 K of the maximum charge air temperature specified by the manufacturer. The temperature of the cooling medium shall be at least 293 K (20°C).

If a test shop system or external blower is used, the charge air temperature shall be set to within $\pm$ 5 K of the maximum charge air temperature specified by the manufacturer at the speed of the declared maximum power and full load. Coolant temperature and coolant flow rate of the charge air cooler at the above set point shall not be changed for the whole test cycle. The charge air cooler volume shall be based upon good engineering practice and typical vehicle/machinery applications.

## 6.3 Power

The basis of specific emissions measurement is uncorrected net power.

Certain auxiliaries necessary only for the operation of the vehicle and which may be mounted on the engine should be removed for the test. The following incomplete list is given as an example:

- air compressor for brakes

- power steering compressor

- air conditioning compressor

- pumps for hydraulic actuators

Where auxiliaries have not been removed, the power absorbed by them shall be determined in order to adjust the set values and to calculate the work produced by the engine over the test cycle.

## 6.4 Engine air intake system

An engine air intake system or a test shop system shall be used presenting an air intake restriction within $\pm$ 300 Pa of the maximum value specified by the manufacturer for a clean air cleaner at the speed of rated power and full load.

## 6.5 Engine air intake system

An engine exhaust system or a test shop system shall be used presenting an exhaust backpressure within $\pm$ 650 Pa of the maximum value specified by the manufacturer at the speed of rated power and full load. The exhaust system shall conform to the requirements for exhaust gas sampling, as set out in 8.3.2.2 and 8.3.3.2.

If the engine is equipped with an exhaust aftertreatment device, the exhaust pipe shall have the same diameter as found in-use for at least 4 pipe diameters upstream to the inlet of the beginning of the expansion section containing the aftertreatment device. The distance from the exhaust manifold flange or turbocharger outlet to the exhaust aftertreatment device shall be the same as in the vehicle configuration or within the distance specifications of the manufacturer. The exhaust backpressure or restriction shall follow the same criteria as above, and may be set with a valve. The aftertreatment container may be removed during dummy tests and during engine mapping, and replaced with an equivalent container having an inactive catalyst support.

## 6.6 Cooling system

An engine cooling system with sufficient capacity to maintain the engine at normal operating temperatures

prescribed by the manufacturer shall be used.

## 6.7    Lubricating oil

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

## 6.8    Specification of the reference fuel

The appropriate reference fuels as defined in Annex 10.3 must be used for testing. Since fuel characteristics influence the engine exhaust gas emission, the characteristics of the fuel used for the test shall be determined, recorded and declared with the results of the test. The reference code and the analysis of the fuel shall be provided.

The fuel temperature shall be in accordance with the manufacturers recommendations

# 7   Test procedures

## 7.1    Principles of emissions measurement

In this regulation, two measurement principles are described that are functionally equivalent: Both principles may be used for both the WHTC and the WHSC cycle:

- the gaseous components are measured in the raw exhaust gas on a real time basis, and the particulates are determined using a partial flow dilution system;

- the gaseous components and the particulates are determined using a full flow dilution system (CVS system).

- any combination of the two principles (e.g. raw gaseous measurement and full flow particulate measurement) is permitted.

The engine shall be subjected to the tests specified below.

## 7.2    Transient test cycle WHTC

The transient test cycle WHTC is listed in Annex 10.2 as a second-by second sequence of normalized speed and torque values applicable to all engines covered by this Standard. In order to perform the test on an engine test cell, the normalized values shall be converted to the actual values for the individual engine under test based on the engine mapping curve. The conversion is referred to as denormalization, and the test cycle so developed as the reference cycle of the engine to be tested. With those reference speed and torque values, the cycle shall be run on the test cell, and the feedback speed, torque and power values shall be recorded. In order to validate the test run, a regression analysis between reference and feedback speed, torque and power values shall be conducted upon completion of the test. For calculation of the brake specific emissions, the actual cycle work shall be calculated by integrating actual engine power over the cycle. For cycle validation, the actual cycle work must be within prescribed limits of the cycle work of the reference cycle (reference cycle work).

The WHTC is shown schematically in figure 2.
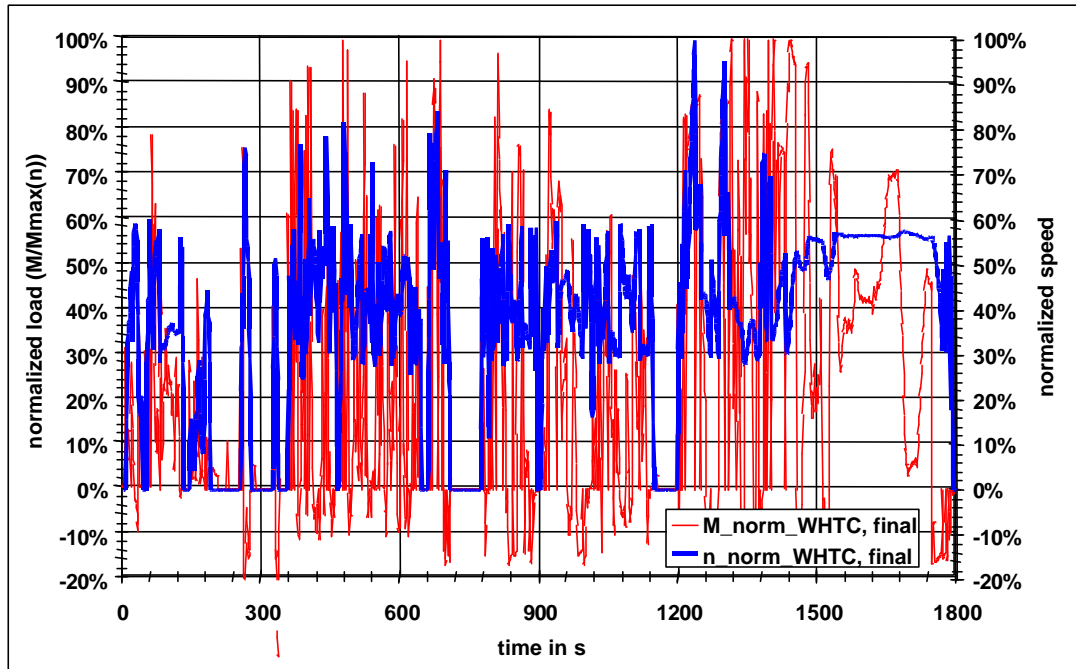


**Figure 2 — WHTC test cycle**

## 7.3    Steady state test cycle WHSC

The steady state test cycle WHSC consists of a number of speed and power modes which cover the typical operating range of heavy duty engines. During each mode and the ramps between the modes the concentration of each gaseous pollutant, exhaust flow and power output shall be determined, and the measured values weighted. The particulate sample shall be diluted with conditioned ambient air. One sample over the complete test procedure shall be taken, and collected on suitable filters.

The WHSC is shown schematically in table 1.

| Basis: | Total PM sampling time close to WHTC = 1520 sec | | | | | |
|---|---|---|---|---|---|---|
| | Mode length dependent on WF (J13 procedure proposed by Mr. Schweizer) | | | | | |
| | Mode stabilization time = 30 sec | | | | | |
| | Idle mode determines length of other modes due to the highest WF (ca. 5,7 minutes) | | | | | |
| | Total cycle length is 31.3 minutes | | | | | |
| | Motoring is accounted for mathematically by a WF of 0.24 and zero emissions/zero power) | | | | | |
| | Motoring does not add to sample time, mode length and cycle length | | | | | |
| | | | | | | |
| Mode No | Speed [%] | Load [%] | WF | Sample time [s] | Mode length [s] | |
| 0 | Motoring | | 24% | | | |
| 1 | 0 | 0 | 17% | 340 | 370 | |
| 2 | 55 | 100 | 2% | 40 | 70 | |
| 3 | 55 | 25 | 10% | 200 | 230 | |
| 4 | 55 | 70 | 3% | 60 | 90 | |
| 5 | 35 | 100 | 2% | 40 | 70 | |
| 6 | 25 | 25 | 8% | 160 | 190 | |
| 7 | 45 | 70 | 3% | 60 | 90 | |
| 8 | 45 | 25 | 6% | 120 | 150 | |
| 9 | 55 | 50 | 5% | 100 | 130 | |
| 10 | 75 | 100 | 2% | 40 | 70 | |
| 11 | 35 | 50 | 8% | 160 | 190 | |
| 12 | 35 | 25 | 10% | 200 | 230 | |
| Sum | | | 100% | 1520 | 1880 | |

**Table 1            WHSC test cycle**

## 7.4 Engine Mapping Procedure

For generating the WHTC and WHSC on the test cell, the engine shall be mapped prior to the run of the test cycle for determining the speed vs. torque curve.

### 7.4.1 Determination of the mapping speed range

The minimum and maximum mapping speeds are defined as follows:

Minimum mapping speed   =   idle speed

Maximum mapping speed   =   $n_{hi}$ * 1,02 or speed where full load torque drops off to zero, whichever is smaller

### 7.4.2 Engine mapping curve

The engine shall be warmed up at maximum power in order to stabilize the engine parameters according to the recommendation of the manufacturer and good engineering practice. When the engine is stabilized, the engine mapping shall be performed according to the following procedure.

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

(b) The engine shall be operated at full load setting of the injection pump at minimum mapping speed.

(c) The engine speed shall be increased at an average rate of  8 ± 1 /min/s from minimum to maximum mapping speed. Engine speed and torque points shall be recorded at a sample rate of at least one point per second.

### 7.4.3 Alternate mapping

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

### 7.4.4 Replicate tests

An engine need not be mapped before each and every test cycle. An engine shall be remapped prior to a test cycle if:
−   an unreasonable amount of time has transpired since the last map, as determined by engineering judgement,
or,
-  physical changes or recalibrations have been made to the engine which may potentially affect engine performance.


## 7.5 Generation of the reference test cycle

### 7.5.1 Denormalization of engine speed

The speed shall be denormalized using the following equation:

Actual speed  = n_norm * (0,45 * n_lo + 0,45 * n_pref + 0,1 * n_hi – n_idle) * 2,0327 + n_idle          (4)


where

n_lo is the lowest speed where the power is 55% of maximum power

n_pref: The integral of the max. torque has to be calculated from n_idle up to n95h in steps of 8 min-1.

n95h is the highest speed where the power is 95% of maximum power

n_pref is then defined as that engine speed, where the max. torque integral is 51% of the whole integral.

n_hi is the highest speed where the power is 70% of maximum power.

n_idle is the idle speed

### 7.5.2    Denormalization of engine torque

The torque values in the engine dynamometer schedule of Annex 10.2  are normalized to the maximum torque at the respective speed. The torque values of the reference cycle shall be denormalized, using the mapping curve determined according to paragraph, as follows:

$$\text{Actual torque} = \frac{\%\,\text{torque} \times \text{max. torque}}{100} \tag{5}$$

for the respective actual speed as determined in 7.5.1.

### 7.5.3    Example of denormalization procedure

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

% speed  =          43 %
% torque  =          82 %

Given the following values:

n_lo      =      1015 /min
n_hi      =      2200 /min
n_pref    =      1300 /min
n_idle    =       600 /min

results in

$$\text{actual speed} = \frac{43 \times (0{,}45 \times 1015 + 0{,}45 \times 1300 + 0{,}1 \times 2200 - 600) \times 2{,}0327}{100} + 600 = 1178 \text{ /min}$$

With the maximum torque of 700 Nm observed from the mapping curve at 1178 /min

$$\text{actual torque} = \frac{82 \times 700}{100} = 574 \text{ Nm}$$

## 7.6    Verification of the test run

### 7.6.1    Data shift

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

### 7.6.2    Calculation of the cycle work

The actual cycle work $W_{act}$ (kWh) shall be calculated using each pair of engine feedback speed and torque values recorded. This shall be done after any feedback data shift has occured, if this option is selected. The actual cycle work $W_{act}$ is used for comparison to the reference cycle work $W_{ref}$ and for calculating the brake specific emissions (see 8.3.2.6) the same methodology shall be used for integrating both reference and actual engine power. If values are to be determined between adjacent reference or adjacent measured values, linear interpolation shall be used.

In integrating the actual cycle work, any negative torque values shall be set equal to zero and included. If integration is performed at a frequency of less than 5 Hertz, and if, during a given time segment, the torque value changes from positive to negative or negative to positive, the negative portion shall be computed and set equal to zero. The positive portion shall be included in the integrated value.

$W_{act}$ shall be between -15 % and + 5 % of $W_{ref}$.

### 7.6.3    Validation statistics of the test cycle

Linear regressions of the feedback values on the reference values shall be performed for speed, torque and power. This shall be done after any feedback data shift has occured, if this option is selected. The method of least squares shall be used, with the best fit equation having the form:

$$y = mx + b \tag{6}$$

where:

| | | |
|---|---|---|
| y = | | feedback (actual) value of speed (min$^{-1}$), torque (Nm), or power (kW) |
| m | = | slope of the regression line |
| x = | | reference value of speed (min$^{-1}$), torque (Nm), or power (kW) |
| b | = | y intercept of the regression line |

The standard error of estimate (SE) of y on x and the coefficient of determination ($r^2$) shall be calculated for each regression line.

It is recommended that this analysis be performed at 1 Hertz. For a test to be considered valid, the criteria of table 2 must be met.

**Table 2        Regression Line Tolerances**

| | Speed | Torque | Power |
|---|---|---|---|
| Standard error of estimate (SE) of Y on X | max 100 min$^{-1}$ | max 13 % of power map maximum engine torque | max 8% of power map maximum engine power |
| Slope of the regression line, m | 0,95 to 1,03 | 0,83 – 1,03 | 0,89 – 1,03 |
| Coefficient of determination, $r^2$ | min 0,9700 | min 0,8800 | min 0,9100 |
| Y intercept of the regression line, b | ± 50 min$^{-1}$ | ± 20 Nm or ± 2 % of max torque whichever is greater | ± 4 kW or ± 2 % of max power whichever is greater |

For regression purposes only, point deletions are permitted where noted in table 3 before doing the regression calculation. However, those points must not be deleted for the calculation of cycle work and emissions. An idle point is defined as a point having a normalized reference torque of 0 % and a normalized reference speed of 0 %. Point deletion may be applied to the whole or to any part of the cycle.

**Table 3        Permitted Point Deletions From Regression Analysis**

| Condition | Points to be deleted |
|---|---|
| First 24 ± 1 seconds and last 25 ± 1 seconds | Speed, torque, power |
| Full load demand and torque feedback < 95% torque reference | Torque and/or power |
| Full load demand and speed feedback < 95% speed reference | Speed and/or power |
| No load, speed feedback > idle speed + 50 min$^{-1}$, and torque feedback > 105 % torque reference | Torque and/or power |
| No load, speed feedback ≤ idle speed + 50 min$^{-1}$, and torque feedback = manufacturer defined/measured idle torque ± 2 % of max. torque | Speed and/or power |
| No load and speed feedback > 105 % speed reference | Speed and/or power |

## 7.7    Emissions Test Run

### 7.7.1    Introduction

The emissions to be measured from the exhaust of the engine include the gaseous components (carbon monoxide, total hydrocarbons or non-methane hydrocarbons and oxides of nitrogen), and the particulates. Additionally, carbon dioxide is often used as a tracer gas for determining the dilution ratio of partial and full

flow dilution systems.

The above pollutants shall be examined during the prescribed test cycles. Using the engine torque and speed feedback signals of the engine dynamometer, the power shall be integrated with respect to time of the cycle resulting in the work produced by the engine over the cycle. The concentrations of the gaseous components shall be determined over the cycle either in the raw exhaust gas by integration of the analyzer signal, or in the diluted exhaust gas of a CVS full flow dilution system by integration or by bag sampling. For particulates, a proportional sample shall be collected from the diluted exhaust gas on a specified filter by either partial flow dilution or full flow dilution. Depending on the method used, the diluted or undiluted exhaust gas flow rate shall be determined over the cycle to calculate the mass emission values of the pollutants. The mass emission values shall be related to the engine work to get the grams of each pollutant emitted per kilowatt hour.

## 7.7.2    Preparation of the sampling filters

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

## 7.7.3    Installation of the measuring equipment

The instrumentation and sample probes shall be installed as required. The tailpipe shall be connected to the full flow dilution system, if used.

## 7.7.4    Starting and preconditioning the dilution system and the engine

The dilution system and the engine shall be started and warmed up. The sampling system shall be preconditioned by operating the engine at a condition of rated speed, 100 percent torque for a minimum of 20 minutes while simultaneously operating either the partial flow dilution system or the full flow dilution system with secondary dilution system. Dummy particulate emissions samples may be collected. Those sample filters need not be stabilized or weighed, and may be discarded. Filter media may be changed during conditioning as long as the total sampled time through the filters and sampling system exceeds 20 minutes. Flow rates shall be set at the approximate flow rates selected for transient testing. Torque shall be reduced from 100 percent torque while maintaining the rated speed condition as necessary to prevent exceeding the 464 K (191 $^{\circ}$ C) maximum sample zone temperature specifications, if a full flow dilution system is used.

## 7.7.5    Starting the particulate sampling system

The particulate sampling system shall be started and running on by-pass. The particulate background level of the dilution air may be determined by sampling the dilution air prior to the entrance of the exhaust gas into the dilution tunnel. If filtered dilution air is used, one measurement may be done prior to or after the test. If the dilution air is not filtered, measurements at the beginning and at the end of the cycle, may be done, and the values averaged. If a different sampling system is used for background measurement, the measurement shall be done over the period of the test run.

## 7.7.6    Adjustment of the dilution system

The total diluted exhaust gas flow of a full flow dilution system or the diluted exhaust gas flow through a partial flow dilution system shall be set to eliminate water condensation in the system, and to obtain a filter face temperature between 315 K (42°C) and 325 K (52°C).

## 7.7.7    Checking the analyzers

The emission analyzers shall be set at zero and spanned. If sample bags are used, they shall be evacuated.

## 7.7.8    Engine starting procedure

The stabilized engine shall be started within 5 min after completion of warm-up according to the manufacturer's recommended starting procedure in the owner's manual, using either a production starter motor or the dynamometer. Optionally, the test may start directly from the engine preconditioning phase without shutting the engine off, within 5 minutes after the engine has been brought to idle condition.

### 7.7.9 Cycle run

#### 7.7.9.1 Test sequence

The test sequence shall be started at the start of the engine or within 5 minutes after the engine has reached idle speed, when starting directly from the preconditioning phase. The test shall be performed according to the reference cycle as set out in 7.5. Engine speed and torque command set points shall be issued at 5 Hz (10 Hz recommended) or greater. The set points shall be calculated by linear interpolation between the 1 Hz set points of the reference cycle. Feedback engine speed and torque shall be recorded at least once every second during the test cycle, and the signals may be electronically filtered.

#### 7.7.9.2 Analyzer response

At the start of the engine or test sequence, if the cycle is started directly from the preconditioning, the measuring equipment shall be started, simultaneously:

- start collecting or analyzing dilution air, if a full flow dilution system is used;

- start collecting or analyzing raw or diluted exhaust gas, depending on the method used;

- start measuring the amount of diluted exhaust gas and the required temperatures and pressures;

- start recording the exhaust gas mass flow rate, if raw exhaust gas analysis is used;

- start recording the feedback data of speed and torque of the dynamometer.

If raw exhaust measurement is used, the emission concentrations (HC, CO and NOx) and the exhaust gas mass flow rate shall be measured continuously and stored with at least 2 Hz on a computer system. All other data may be recorded with a sample rate of at least 1 Hz. For analog analyzers the response shall be recorded, and the calibration data may be applied online or offline during the data evaluation.

If a full flow dilution system is used, HC and $NO_x$ shall be measured continuously in the dilution tunnel with a frequency of at least 2 Hz. The average concentrations shall be determined by integrating the analyzer signals over the test cycle. The system response time shall be no greater than 20 s, and shall be coordinated with CVS flow fluctuations and sampling time/test cycle offsets, if necessary. CO, $CO_2$, and NMHC shall be determined by integration or by analyzing the concentrations in the sample bag, collected over the cycle. The concentrations of the gaseous pollutants in the dilution air shall be determined by integration or by collecting into the background bag. All other parameters that need to be measured shall be recorded with a minimum of one measurement per second (1 Hz).

#### 7.7.9.3 Particulate sampling

At the start of the engine or test sequence, if the cycle is started directly from the preconditioning, the particulate sampling system shall be switched from by-pass to collecting particulates.

If a partial flow dilution system is used, the sample pump(s) shall be adjusted so that the flow rate through the particulate sample probe or transfer tube is maintained proportional to the exhaust mass flow rate.

If a full flow dilution system is used, the sample pump(s) shall be adjusted so that the flow rate through the particulate sample probe or transfer tube is maintained at a value within ± 5 % of the set flow rate. If flow compensation (i.e., proportional control of sample flow) is used, it must be demonstrated that the ratio of main tunnel flow to particulate sample flow does not change by more than ± 5 % of its set value (except for the first 10 seconds of sampling). The average temperature and pressure at the gas meter(s) or flow instrumentation inlet shall be recorded. If the set flow rate cannot be maintained over the complete cycle (within ± 5 %) because of high particulate loading on the filter, the test shall be voided. The test shall be rerun using a lower flow rate and/or a larger diameter filter.

#### 7.7.9.4 Engine stalling

If the engine stalls anywhere during the test cycle, the engine shall be preconditioned and restarted, and the test repeated. If a malfunction occurs in any of the required test equipment during the test cycle, the test shall be voided.

#### 7.7.9.5 Operations after test

At the completion of the test, the measurement of the exhaust gas mass flow rate, the diluted exhaust gas volume, the gas flow into the collecting bags and the particulate sample pump shall be stopped. For an integrating analyzer system, sampling shall continue until system response times have elapsed.

The concentrations of the collecting bags, if used, shall be analyzed as soon as possible and in any case not

later than 20 minutes after the end of the test cycle.

After the emission test, a zero gas and the same span gas shall be used for re-checking the analyzers. The test will be considered acceptable if the difference between the pre-test and post-test results is less than 2 % of the span gas value.

The particulate filters shall be returned to the weighing chamber no later than one hour after completion of the test. They shall be conditioned in a petri dish, which is protected against dust contamination and allows air exchange, for at least one hour, and then weighed. The gross weight of the filters shall be recorded.

# 8  Emissions Measurement and Calculation

## 8.1    Dry/wet correction

If the emissions are not measured on a wet basis the measured concentration shall be converted to a wet basis according to either of the following formulae.

$$c_w = K_W \times c_d \tag{7}$$

a)        For the raw exhaust gas:

$$k_W = \left(1 - \frac{1{,}2434 \times H_a + 111{,}12 \times w_{ALF} \times \frac{q_{mf,i}}{q_{madj}}}{773{,}4 + 1{,}2434 \times H_a + \frac{q_{mf,i}}{q_{madj}} \times k_f \times 1000}\right) \times 1{,}008 \tag{8}$$

or

$$k_W = \left(1 - \frac{1{,}2434 \times H_a + 111{,}12 \times w_{ALF} \times \frac{q_{mf,i}}{q_{madj}}}{773{,}4 + 1{,}2434 \times H_a + \frac{q_{mf,i}}{q_{madj}} \times k_f \times 1000}\right) \Bigg/ \left(1 - \frac{p_r}{p_b}\right) \tag{9}$$

b)        For the diluted exhaust gas:

$$K_{We1} = \left(1 - \frac{\alpha \times \% \, c_{wCO2}}{200}\right) - K_{W1} \tag{10}$$

or

$$K_{We2} = \left(\frac{(1 - K_{W1})}{1 + \frac{\alpha \times \% \, c_{dCO2}}{200}}\right) \tag{11}$$

c)        For the dilution air

$$K_{Wd} = 1 - K_{W1} \tag{12}$$

$$K_{W1} = \frac{1,608 \times \left[ H_d \times \left(1 - \frac{1}{D}\right) + H_a \times \left(\frac{1}{D}\right)\right]}{1000 + \left\{1,608 \times \left[ H_d \times \left(1 - \frac{1}{D}\right) + H_a \times \left(\frac{1}{D}\right)\right]\right\}}$$

(13

where

| | | |
|---|---|---|
| $p_r$ | = | Water vapor pressure after cooling bath, kPa |
| $p_b$ | = | Total atmospheric pressure, kPa |
| **a** | = | molar hydrogen ratio of the fuel |
| $c_{CO2}$ | = | dry $CO_2$ concentration, % |
| $c_{CO}$ | = | dry CO concentration, % |
| $H_a$ | = | intake air humidity, g water per kg dry air |
| $H_d$ | = | dilution air humidity, g water per kg dry air |
| $k_f$ | = | $0,055584 \times w_{ALF} - 0,0001083 \times w_{BET} - 0,0001562 \times w_{GAM} + 0,0079936 \times w_{DEL} +$ |

$0,0069978 \times w_{EPS}$     (14)

NOTE    Equations 8 and 9 are principally identical with the factor 1,008 in equation 8 being an approximation for the more accurate denominator in equation 9.

## 8.2   NO$_x$ correction for humidity and temperature

As the NO$_x$ emission depends on ambient air conditions, the NO$_x$ concentration shall be corrected for humidity and ambient air temperature with the factors given in either of the following formulae.

*a) for compression ignition engines*

$$k_{h,D} = \frac{1}{1 - 0,0182 \times \left(H_a - 10,71\right) + 0,0045 \times \left(T_a - 298\right)}$$

(15)

with:

| | | |
|---|---|---|
| $T_a$ | = | temperature of the intake air, K |
| $H_a$ | = | humidity of the intake air, g water per kg dry air |

*b) for spark ignition engines*

$k_{h,G}$          $= 0,6272 + 44,030 \times 10^{-3} \times H_a - 0,862 \times 10^{-3} \times H_a^2$     (16)

where $H_a$ may be derived from relative humidity measurement, dewpoint measurement, vapor pressure measurement or dry/wet bulb measurement using the generally accepted formulae.

## 8.3   Partial Flow Dilution (PFS) and Raw Gaseous Measurement

The instantaneous concentration signals of the gaseous components are used for the calculation of the mass emissions by multiplication with the instantaneous exhaust mass flow rate. The exhaust mass flow rate may be measured directly, or calculated using the methods of intake air and fuel flow measurement, tracer method or intake air and air/fuel ratio measurement. Special attention shall be paid to the reponse times of the different instruments. These differences shall be accounted for by time aligning the signals.

For particulates, the exhaust mass flow rate signals are used for controlling the partial flow dilution system to take a sample proportional to the exhaust mass flow rate. The quality of proportionality is checked by applying a regression analysis between sample and exhaust flow.

The complete test set up is schematically shown in figure 3.
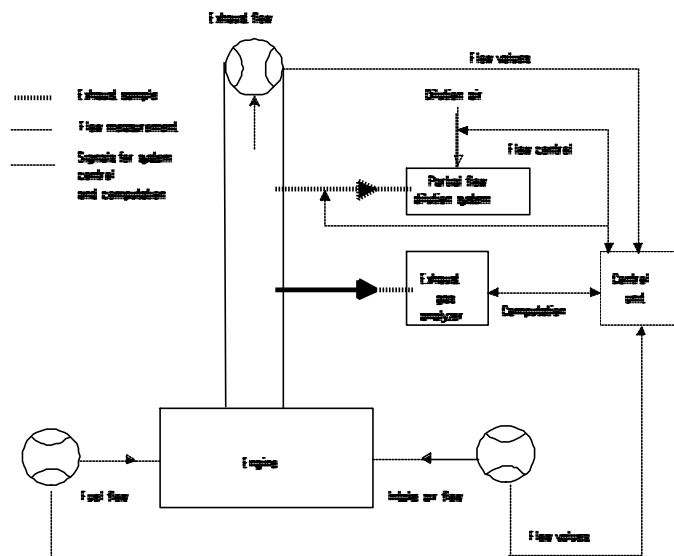
**Figure 3       Schematic of raw/partial flow measurement system**

## 8.3.1     Determination of exhaust gas mass flow

### 8.3.1.1            Introduction

For calculation of the emissions in the raw exhaust gas and for controlling of a partial flow dilution system, it is necessary to know the exhaust gas mass flow rate. For the determination of the exhaust mass flow rate, either of the methods described in 8.3.1.3 to 8.3.1.6 may be used.

### 8.3.1.2            Response time

For the purpose of emissions calculation, the response time of either method described below shall be equal to or less than the requirement for the analyzer response time, as defined in 9.3.3.5 .

For the purpose of controlling of a partial flow dilution system, a faster response is required. For partial flow dilution systems with online control, a response time of $\leq 0,3$ seconds is required. For partial flow dilution systems with look ahead control based on a pre-recorded test run, a response time of the exhaust flow measurement system of $\leq 5$ seconds with a rise time of $\leq 1$ second is required. The system response time shall be specified by the instrument manufacturer. The combined response time requirements for exhaust gas flow and partial flow dilution system are indicated in 8.3.3.3.

### 8.3.1.3            Direct measurement method

Direct measurement of the instantaneous exhaust flow may be done by systems, such as:

- pressure differential devices, like flow nozzle, (details see ISO 5167)

- ultrasonic flowmeter

- vortex flowmeter

Precautions shall be taken to avoid measurement errors which will impact emission value errors. Such precautions include the careful installation of the device in the engine exhaust system according to the instrument manufacturers' recommendations and to good engineering practice. Especially, engine performance and emissions must not be affected by the installation of the device.

The flowmeters shall meet the accuracy specifications of 9.2.

### 8.3.1.4            Air and fuel measurement method

This involves measurement of the air flow and the fuel flow with suitable flowmeters. The calculation of the instantaneous exhaust gas flow is as follows:

$$q_{mew,i} = q_{maw,i} + q_{mf,i} \text{ (for wet exhaust mass)} \tag{17}$$

The flowmeters shall meet the accuracy specifications of 9.2 , but shall be accurate enough to also meet the accuracy specifications for the exhaust gas flow.

### 8.3.1.5 Tracer measurement method

This involves measurement of the concentration of a tracer gas in the exhaust.

A known amount of an inert gas (e.g. pure helium) shall be injected into the exhaust gas flow as a tracer. The gas is mixed and diluted by the exhaust gas, but shall not react in the exhaust pipe. The concentration of the gas shall then be measured in the exhaust gas sample.

In order to ensure complete mixing of the tracer gas, the exhaust gas sampling probe shall be located at least 1 m or 30 times the diameter of the exhaust pipe, whichever is larger, downstream of the tracer gas injection point. The sampling probe may be located closer to the injection point if complete mixing is verified by comparing the tracer gas concentration with the reference concentration when the tracer gas is injected upstream of the engine.

The tracer gas flow rate shall be set so that the tracer gas concentration at engine idle speed after mixing becomes lower than the full scale of the trace gas analyzer.

The calculation of the exhaust gas flow is as follows:

$$q_{mewi} = \frac{q_{vt} \times r_e}{60 \times \left(c_{mix,i} - c_a\right)}$$

(18

where

| | | |
|---|---|---|
| $q_{mew,i}$ | = | instantaneous exhaust mass flow, kg/s |
| $q_{vt}$ | = | tracer gas flow,  cm³/min |
| $c_{mix,i}$ | = | instantaneous concentration of the tracer gas after mixing, ppm |
| $r_e$ | = | density of the exhaust gas, kg/m³ (cf. table 3) |
| $c_a$ | = | background concentration of the tracer gas in the intake air, ppm |

The background concentration of the tracer gas ($c_a$) may be determined by averaging the background concentration measured immediately before the test run and after the test run.

When the background concentration is less than 1% of the concentration of the tracer gas after mixing ($c_{mix,i}$) at maximum exhaust flow, the background concentration may be neglected.

The total system shall meet the accuracy specifications for the exhaust gas flow, and shall be calibrated according to 9.3.3.8.

### 8.3.1.6 Air flow and air to fuel ratio measurement method

This involves exhaust mass calculation from the air flow and the air to fuel ratio. The calculation of the instantaneous exhaust gas mass flow is as follows:

$$q_{mewi} = q_{mawi} \times \left(1 + \frac{1}{A/F_{st} \times l_i}\right)$$

(19

with

$$A/F_{st} = \frac{138,0 \times \left(\beta + \frac{a}{4} - \frac{e}{2} + ?\right)}{12,011 \times \beta + 1,00794 \times a + 15,9994 \times e + 14,0067 \times d + 32,065 \times ?}$$

$$l_i = \frac{\beta \times \left(100 - \frac{c_{CO} \times 10^{-4}}{2} - c_{HC} \times 10^{-4}\right) + \left(\frac{a}{4} \times \frac{1 - \frac{2 \times c_{CO} \times 10^{-4}}{3,5 \times c_{CO2}}}{1 + \frac{c_{CO} \times 10^{-4}}{3,5 \times c_{CO2}}} - \frac{e}{2} - \frac{d}{2}\right) \times \left(c_{CO2} + c_{CO} \times 10^{-4}\right)}{4,764 \times \left(\beta + \frac{a}{4} - \frac{e}{2} + ?\right) \times \left(c_{CO2} + c_{CO} \times 10^{-4} + c_{HC} \times 10^{-4}\right)}$$

where

| | | | |
|---|---|---|---|
| | $A/F_{st}$ | = | stoichiometric air to fuel ratio, kg/kg |
| | $l$ | = | excess air ratio |
| | $c_{CO2}$ | = | dry $CO_2$ concentration, % |
| | $c_{CO}$ | = | dry CO concentration, ppm |
| | $c_{HC}$ | = | HC concentration, ppm |

NOTE          $b$ can be 1 for fuels containing carbon and 0 for hydrogen fuel.

The air flowmeter shall meet the accuracy specifications of 9.2, the $CO_2$ analyzer used shall meet the specifications of 9.3.1, and the total system shall meet the accuracy specifications for the exhaust gas flow.

Optionally, air to fuel ratio measurement equipment such as a zirconia type sensor may be used for the measurement of the excess air ratio which meets the specifications of 9.3.2.7.

## 8.3.2      Determination of the gaseous components

### 8.3.2.1          Introduction

The gaseous components emitted by the engine submitted for testing shall be measured by the methods described in 9.3. They shall be determined in the raw exhaust gas. Data evaluation and calculation procedures are described in 8.4.2.3 and 8.3.2.4.

### 8.3.2.2          Sampling for gaseous emissions

The gaseous emissions sampling probes shall be fitted at least 0,5 m or 3 times the diameter of the exhaust pipe - whichever is the larger - upstream of the exit of the exhaust gas system  but sufficiently close to the engine as to ensure an exhaust gas temperature of at least 343 K (70°C) at the probe.

In the case of a multi-cylinder engine with a branched exhaust manifold, the inlet of the probe shall be located sufficiently far downstream so as to ensure that the sample is representative of the average exhaust emissions from all cylinders. In multi-cylinder engines having distinct groups of manifolds, such as in a "Vee" engine configuration, it is recommended to combine the manifolds upstream of the sampling probe. If this is not practical, it is permissible to acquire a sample from the group with the highest $CO_2$ emission. Other methods which have been shown to correlate with the above methods may be used. For exhaust emission calculation the total exhaust mass flow shall be used.

If the engine is equipped with an exhaust aftertreatment system, the exhaust sample shall be taken downstream of the exhaust aftertreatment system.

### 8.3.2.3          Data evaluation

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

For calculation of the mass emission of the gaseous components the traces of the recorded concentrations and the trace of the exhaust gas mass flow rate shall be time aligned by the transformation time as defined in 3.1. Therefore, the response time of each gaseous emissions analyzer and of the exhaust gas mass flow system shall be determined according to 8.3.1.2 and 9.3.3.5, respectively, and recorded.

### 8.3.2.4          Calculation of mass emission

The mass of the pollutants (g/test) shall be preferably determined by calculating the instantaneous mass emissions from the raw concentrations of the pollutants, the u values from table 4 and the exhaust mass flow, aligned for the transformation time as determined in accordance with 8.3.2.3, and integrating the instantaneous values over the cycle in accordance with equation 20. If measured on a dry basis, the dry/wet correction according to 8.1 shall be applied to the instantaneous concentration values before any further calculation is done.

An example of the calculation procedures is given in Annex 10.6.

The following formulae shall be applied.

a) for the WHTC

$$m_{gas} = \sum_{i=1}^{i=n} u_{gas} \times c_{gas i} \times q_{mewi} \times \frac{1}{f} \qquad \text{(in g/test)} \qquad (22)$$

where

| | | |
|---|---|---|
| $u_{gas}$ | = | ratio between density of exhaust component and density of exhaust gas |
| $c_{gas,i}$ | = | instantaneous concentration of the component in the raw exhaust gas, ppm |
| $q_{mew,i}$ | = | instantaneous exhaust mass flow, kg/s |
| $f$ | = | data sampling rate, Hz |
| $n$ | = | number of measurements |

b) for each mode of the WHSC

$$m_{gas} = u_{gas} \times c_{gas} \times q_{mew} \qquad \text{(in g/h)} \qquad (23)$$

where

| | | |
|---|---|---|
| $u_{gas}$ | = | ratio between density of exhaust component and density of exhaust gas |
| $c_{gas}$ | = | concentration of the respective component in the raw exhaust gas, ppm |
| $q_{mew}$ | = | exhaust gas mass flow rate, kg/s |

For the calculation of $NO_x$, the humidity correction factor $k_{h,D}$, or $k_{h,G}$, as applicable, as determined according to 8.2, shall be used.

The measured concentration shall be converted to a wet basis according to 8.1, if not already measured on a wet basis

Values for $u$ are given in table 4 below for selected components and a range of fuels:

### Table 4 Values of $u$ in the raw exhaust gas and density for various exhaust components

| Gas | | $NO_x$ | CO | HC | $CO_2$ | $O_2$ | $CH_4$ | HCHO | $CH_3OH$ |
|---|---|---|---|---|---|---|---|---|---|
| $r_{gas}$ [kg/m³] | | 2,053 | 1,250 | a) | 1,9636 | 1,4277 | 0,716 | 1,340 | 1,430 |
| FUEL | $r_e$ | Coefficient $u_{gas}$ b) | | | | | | | |
| Diesel | 1,2939 | 0,001587 | 0,000966 | 0,000479 | 0,001518 | 0,001103 | 0,000553 | 0,001035 | 0,001105 |
| RME | 1,2950 | 0,001585 | 0,000965 | 0,000536 | 0,001516 | 0,001102 | 0,000553 | 0,001035 | 0,001104 |
| Methanol | 1,2607 | 0,001628 | 0,000991 | 0,001133 | 0,001558 | 0,001132 | 0,000568 | 0,001063 | 0,001134 |
| Ethanol | 1,2756 | 0,001609 | 0,000980 | 0,000805 | 0,001539 | 0,001119 | 0,000561 | 0,001050 | 0,001121 |
| Natural Gas c) | 1,2656 | 0,001622 | 0,000987 | 0,000523 d) | 0,001552 | 0,001128 | 0,000565 | 0,001059 | 0,001130 |
| Propane | 1,2805 | 0,001603 | 0,000976 | 0,000511 | 0,001533 | 0,001115 | 0,000559 | 0,001046 | 0,001116 |
| Butane | 1,2831 | 0,001600 | 0,000974 | 0,000505 | 0,001530 | 0,001113 | 0,000558 | 0,001044 | 0,001114 |
| Gasoline | 1,2977 | 0,001582 | 0,000963 | 0,000471 | 0,001513 | 0,001100 | 0,000551 | 0,001032 | 0,001102 |

a) depending on fuel
b) at $l$ = 2, dry air, 273 K, 101,3 kPa
c) $u$ accurate within 0,2 % for mass composition of: C = 66 - 76 %; H = 22 - 25 %; N = 0 - 12 %
d) NMHC on the basis of $CH_{2,93}$ (for total HC the $u_{gas}$ coefficient of $CH_4$ shall be used)

### 8.3.2.5 Calculation of NMHC and $CH_4$ with the non-methane cutter

The concentration of NMHC and $CH_4$ shall be calculated as follows:

$$c_{NMHC} = \frac{c_{HC(w/oCutter)} \times (1 - E_M) - c_{HC(w/Cutter)}}{E_E - E_M} \qquad (24)$$

$$c_{CH4} = \frac{c_{HC(w/Cutter)} - c_{HC(w/oCutter)} \times (1 - E_E)}{E_E - E_M} \qquad (25)$$

where:

| | | |
|---|---|---|
| $c_{HC(w/Cutter)}$ | = | HC concentration with the sample gas flowing through the NMC |
| $c_{HC(w/oCutter)}$ | = | HC concentration with the sample gas bypassing the NMC |

| $E_M$ | = | methane efficiency as determined per 9.3.3.11.1 |
| $E_E$ | = | ethane efficiency as determined per 9.3.3.11.2 |

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

### 8.3.2.6        Calculation of the specific emissions

The emissions (g/kWh) shall be calculated for each individual component in the following way:

a)        for the WHTC

$$M_{gas} = m_{gas}/W_{act} \tag{26}$$

where

$W_{act}$    =    actual cycle work as determined according to 7.6.2, kWh

b)        for the WHSC

$$GAS_x = \frac{\sum_{i=1}^{i=n}\left(M_{GASi} \times W_{Fi}\right)}{\sum_{i=1}^{i=n}\left(P_i \times W_{Fi}\right)} \tag{27}$$

where

$m_{gas}$    is the mass of individual gas

$P_i$        is the measured power of the individual mode

## 8.3.3    Particulate determination

### 8.3.3.1        Introduction

The determination of the particulates requires a dilution system. In this section, dilution shall be accomplished by a partial flow dilution system. The dilution system shall be set to completely eliminate water condensation in the dilution and sampling systems, and maintain the temperature of the diluted exhaust gas between 315 K (42°C) and 325 K (52°C) immediately upstream of the filter holders. Dehumidifying the dilution air before entering the dilution system is permitted, and especially useful if dilution air humidity is high. The temperature of the dilution air shall be higher than 288 K (15°C) in close proximity to the entrance into the dilution tunnel.

The partial flow dilution system has to be designed to extract a proportional raw exhaust sample  from the engine exhaust stream, thus  responding to excursions in the exhaust stream flow rate, and introduce dilution air to this sample to achieve a temperature between 315 K (42°C) and 325 K (52°C) at the test filter. For this it is essential that the dilution ratio or the sampling ratio $r_{dil}$ or $r_s$ be determined such that the accuracy requirements of 9.4.4 are fulfilled. Different extraction methods can be applied, whereby the type of extraction used dictates to a significant degree the sampling hardware and procedures to be used.

To determine the mass of the particulates, a particulate sampling system, particulate sampling filters, a microgram balance, and a temperature and humidity controlled weighing chamber, are required. The details of the system are described in 9.4.

### 8.3.3.2        Particulate sampling

In general, the particulate sampling probe shall be installed in close proximity to the gaseous emissions sampling probe, but sufficiently distant as to not cause interference. Therefore, the installation provisions of 8.3.2.2 also apply to particulate sampling. The sampling line shall conform to the requirements of 9.3.4.3.

In the case of a multi-cylinder engine with a branched exhaust manifold, the inlet of the probe shall be located sufficiently far downstream so as to ensure that the sample is representative of the average exhaust emissions from all cylinders. In multi-cylinder engines having distinct groups of manifolds, such as in a "Vee" engine configuration, it is recommended to combine the manifolds upstream of the sampling probe. If this is not practical, it is permissible to acquire a sample from the group with the highest particulate emission. Other methods which have been shown to correlate with the above methods may be used. For exhaust emission

calculation the total exhaust mass flow shall be used.

### 8.3.3.3 System response time

For the control of a partial flow dilution system, a fast system response is required. The transformation time for the system shall be determined by the procedure in 9.6.3. If the combined transformation time of the exhaust flow measurement (see 8.3.1.2) and the partial flow system is less than 0,3 sec, online control may be used. If the transformation time exceeds 0,3 sec, look ahead control based on a pre-recorded test run must be used. In this case, the rise time shall be $\leq 1$ sec and the delay time of the combination $\leq 10$ sec.

The total system response shall be designed as to ensure a representative sample of the particulates, $q_{mp,i}$, proportional to the exhaust mass flow. To determine the proportionality, a regression analysis of $q_{mp,i}$ versus $q_{mew,i}$ shall be conducted on a minimum 5 Hz data acquisition rate, and the following criteria shall be met:

- The correlation coefficient $r^2$ of the linear regression between $q_{mp,i}$ and $q_{mew,i}$ shall not be less than 0,95
- The standard error of estimate of $q_{mp,i}$ on $q_{mew,i}$ shall not exceed 5 % of $q_{mp}$ maximum.
- $q_{mp}$ intercept of the regression line shall not exceed $\pm 2$ % of $q_{mp}$ maximum."

Optionally, a pretest may be run, and the exhaust mass flow signal of the pretest be used for controlling the sample flow into the particulate system ("look-ahead control"). Such a procedure is required if the transformation time of the particulate system, $t_{50,P}$ or/and the transformation time of the exhaust mass flow signal, $t_{50,F}$ are > 0,3 sec. A correct control of the partial dilution system is obtained, if the time trace of $q_{mew,pre}$ of the pretest, which controls $q_{mp}$, is shifted by a "look-ahead" time of $t_{50,P} + t_{50,F}$ .

For establishing the correlation between $q_{mp,i}$ and $q_{mew,i}$ the data taken during the actual test shall be used, with $q_{mew,i}$ time aligned by $t_{50,F}$ relative to $q_{mp,i}$ (no contribution from $t_{50,P}$ to the time alignment). That is, the time shift between $q_{mew}$ and $q_{mp}$ is the difference in their transformation times that were determined in 9.6.3

### 8.3.3.4 Data evaluation

The tare weight of the filter, as determined according to clause 7.7.2, shall be subtracted from the gross weight of the filter, as determined according to clause 7.7.9.5, which results in the particulate sample mass $m_f$. For the evaluation of the particulate concentration, the total sample mass ($m_{sep}$) through the filters over the test cycle shall be recorded.

With the prior approval of the parties involved, the particulate mass may be corrected for the particulate level of the dilution air, as determined in clause 7.7.5, in line with good engineering practice and the specific design features of the particulate measurement system used.

### 8.3.3.5 Calculation of mass emission

The mass of particulates (g/test) shall be calculated by either of the following methods. An example of the calculation procedures is given in Annex 10.6.

a)

$$m_{PM} = \frac{m_f}{m_{sep}} \times \frac{m_{edf}}{1000} \tag{28}$$

where

| | | |
|---|---|---|
| $m_f$ | = | particulate mass sampled over the cycle, mg |
| $m_{sep}$ | = | mass of diluted exhaust gas passing the particulate collection filters, kg |
| $m_{edf}$ | = | mass of equivalent diluted exhaust gas over the cycle, kg |

The total mass of equivalent diluted exhaust gas mass over the cycle shall be determined as follows:

$$m_{edf} = \sum_{i=1}^{i=n} q_{medf,i} \times \frac{1}{f} \tag{29}$$

$$q_{medf,i} = q_{mew,i} \times r_{dil,i} \tag{30}$$

$$r_{\text{dil,i}} = \frac{q_{m\text{dew,i}}}{\left(q_{m\text{dew,i}} - q_{m\text{dw,i}}\right)}$$ (31)

where

$q_{m\text{edf,i}}$ = instantaneous equivalent diluted exhaust mass flow rate, kg/s
$q_{m\text{ew,i}}$ = instantaneous exhaust mass flow rate, kg/s
$r_{\text{dil,i}}$ = instantaneous dilution ratio
$q_{m\text{dew,i}}$ = instantaneous diluted exhaust mass flow rate through dilution tunnel, kg/s
$q_{m\text{dw,i}}$ = instantaneous dilution air mass flow rate, kg/s
$f$ = data sampling rate, Hz
$n$ = number of measurements

b)

$$m_{\text{PM}} = m_{\text{f}} / (r_{\text{s}} \times 1000)$$ (32)

where

$m_{\text{f}}$ = particulate mass sampled over the cycle, mg
$r_{\text{s}}$ = average sample ratio over the test cycle

with

$$r_{\text{s}} = \frac{m_{\text{se}}}{m_{\text{ew}}} \times \frac{m_{\text{sep}}}{m_{\text{sed}}}$$ (33)

where

$m_{\text{se}}$ = sample mass over the cycle, kg
$m_{\text{ew}}$ = total exhaust mass flow over the cycle, kg
$m_{\text{sep}}$ = mass of diluted exhaust gas passing the particulate collection filters, kg
$m_{\text{sed}}$ = mass of diluted exhaust gas passing the dilution tunnel, kg

NOTE    In case of the total sampling type system, $m_{\text{sep}}$ and $M_{\text{sed}}$ are identical.

### 8.3.3.6          Calculation of the specific emissions

The particulate emission (g/kWh) shall be calculated in the following way:

a)          for the WHTC

$$M_{\text{PM}} = m_{\text{PM}} / W_{\text{act}}$$ (34)

where

$m_{\text{PM}}$ = particulate mass sampled over the cycle
$W_{\text{act}}$ = actual cycle work as determined according to 7.6.2, kWh

b)          for the WHSC

$$PT = \frac{PT_{mass}}{\sum_{i=1}^{i=n} P_i \times W_{fi}}$$ (35

where

$PT_{mass}$        is the particulate mass sampled over the cycle

$P_i$                is the measured power of the individual mode

### 8.3.3.7 Effective weighting factor (WHSC only)

For the WHSC, the effective weighting factor $W_{FEi}$, for each mode shall be calculated in the following way.

$$W_{fei} = \frac{m_{sepi} \times \overline{q_{medf}}}{m_{sep} \times q_{medfi}}$$

(36

$i = 1, ... n$

The value of the effective weighting factors shall be within ± 0,005 (absolute value) of the weighting factors listed in 7.3.

## 8.4 Full Flow Dilution Measurement (CVS)

The concentration signals, either by integration over the cycle or by bag sampling, of the gaseous components shall be used for the calculation of the mass emissions by multiplication with the diluted exhaust mass flow rate. The exhaust mass flow rate shall be measured with a constant volume sampling (CVS) system, which may use a positive displacement pump (PDP), a critical flow venturi (CFV) or a subsonic venturi (SSV).

For particulates, a proportional sample is taken from the diluted exhaust gas of the CVS system.

The complete test set up is schematically shown in figure 4.
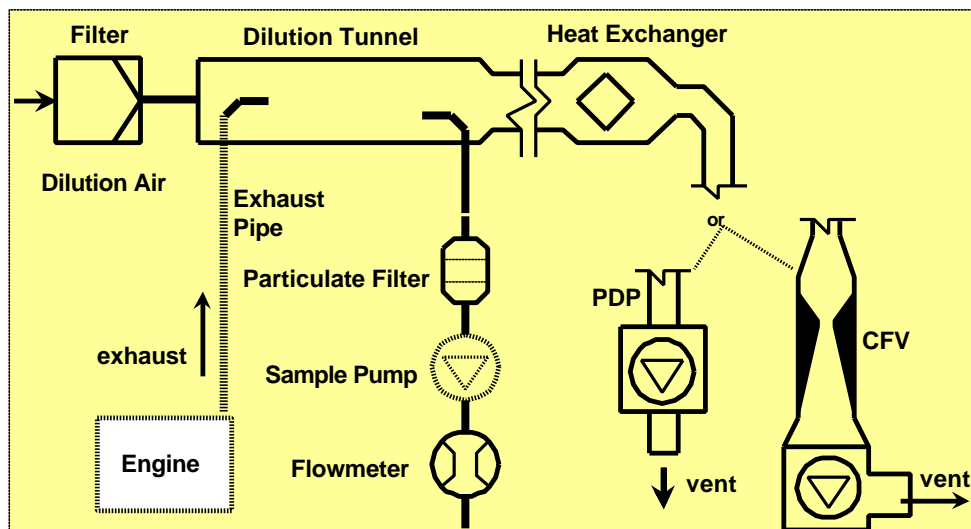


**Figure 4    Schematic of CVS full flow dilution system**

### 8.4.1 Determination of the diluted exhaust gas flow

#### 8.4.1.1 Introduction

For calculation of the emissions in the diluted exhaust gas, it is necessary to know the diluted exhaust gas mass flow rate. The total diluted exhaust gas flow over the cycle (kg/test) shall be calculated from the measurement values over the cycle and the corresponding calibration data of the flow measurement device ($V_0$ for PDP, $K_V$ for CFV, $C_d$, $Y$ for SSV) by either of the methods described in 8.4.1.2 to 8.4.1.4 may be used. If the total sample mass of particulates ($m_{sep}$) and gaseous pollutants exceeds 0,5 % of the total CVS flow ($m_{ed}$), the CVS flow shall be corrected for $m_{sep}$ or the particulate sample flow shall be returned to the CVS prior to the flow measuring device.

### 8.4.1.2 PDP-CVS system

The calculation of the mass flow over the cycle is as follows, if the temperature of the diluted exhaust is kept within ± 6 K over the cycle by using a heat exchanger:

$$m_{ed} = 1{,}293 * V_0 * N_P * (p_B - p_1) * 273 / (101{,}3 * T) \tag{37}$$

where

| | | |
|---|---|---|
| $V_0$ | = | volume of gas pumped per revolution under test conditions, m³/rev |
| $N_P$ | = | total revolutions of pump per test |
| $p_B$ | = | atmospheric pressure in the test cell, kPa |
| $p_1$ | = | pressure depression below atmospheric at pump inlet, kPa |
| T | = | average temperature of the diluted exhaust gas at pump inlet over the cycle, K |

If a system with flow compensation is used (i.e. without heat exchanger), the instantaneous mass emissions shall be calculated and integrated over the cycle. In this case, the instantaneous mass of the diluted exhaust gas shall be calculated as follows:

$$m_{ed,i} = 1{,}293 * V_0 * N_{P,i} * (p_B - p_1) * 273 / (101{,}3 \cdot T) \tag{38}$$

$N_{P,i}$ = total revolutions of pump per time interval

### 8.4.1.3 CFV-CVS system

The calculation of the mass flow over the cycle is as follows, if the temperature of the diluted exhaust is kept within ± 11K over the cycle by using a heat exchanger:

$$m_{ed} = 1{,}293 * t * K_v * p_A / T^{0,5} \tag{39}$$

where

| | | |
|---|---|---|
| t | = | cycle time, s |
| $K_V$ | = | calibration coefficient of the critical flow venturi for standard conditions, |
| $p_A$ | = | absolute pressure at venturi inlet, kPa |
| T | = | absolute temperature at venturi inlet, K |

If a system with flow compensation is used (i.e. without heat exchanger), the instantaneous mass emissions shall be calculated and integrated over the cycle. In this case, the instantaneous mass of the diluted exhaust gas shall be calculated as follows:

$$m_{ed,i} = 1{,}293 * \Delta t_i * K_V * p_A / T^{0,5} \tag{40}$$

where

$\Delta t_i$ = time interval, s

### 8.4.1.4 SSV-CVS system

The calculation of the mass flow over the cycle is as follows, if the temperature of the diluted exhaust is kept within ± 11K over the cycle by using a heat exchanger::

$$m_{ed} = 1{,}293 * Q_{SSV} \tag{41}$$

where

$$Q_{SSV} = A_0 d^2 C_d P_A \sqrt{\left[\frac{1}{T}\left(r^{1.4286} - r^{1.7143}\right) \cdot \left(\frac{1}{1 - \boldsymbol{b}^4 r^{1.4286}}\right)\right]} \tag{42}$$

with

$A_0$ = collection of constants and units conversions

= 0,006111 in SI units of $\left(\dfrac{m^3}{min}\right)\left(\dfrac{K^{\frac{1}{2}}}{kPa}\right)\left(\dfrac{1}{mm^2}\right)$

d = diameter of the SSV throat, m

$C_d$ = discharge coefficient of the SSV

$P_A$ = absolute pressure at venturi inlet, kPa

T = temperature at the venturi inlet, K

r = ratio of the SSV throat to inlet absolute, static pressure = $1 - \dfrac{\Delta P}{P_A}$

r = ratio of the SSV throat diameter, d, to the inlet pipe inner diameter = $\dfrac{d}{D}$

If a system with flow compensation is used (i.e. without heat exchanger), the instantaneous mass emissions shall be calculated and integrated over the cycle. In this case, the instantaneous mass of the diluted exhaust gas shall be calculated as follows:

$$m_{ed} \qquad = \qquad 1{,}293 * Q_{SSV} * \Delta t_i \qquad\qquad (43)$$

where

$$Q_{SSV} = A_0 d^2 C_d P_A * \sqrt{\left[\frac{1}{T}\left(r^{1.4286} - r^{1.7143}\right)\left(\frac{1}{1 - \boldsymbol{b}^4 r^{1.4286}}\right)\right]} \qquad\qquad (44)$$

$\Delta t_i$ = time interval, s

The real time calculation shall be initialized with either a reasonable value for $C_d$, such as 0.98, or a reasonable value of $Q_{ssv}$. If the calculation is initialized with $Q_{ssv}$, the initial value of $Q_{ssv}$ shall be used to evaluate Re.

During all emissions tests, the Reynolds number at the SSV throat must be in the range of Reynolds numbers used to derive the calibration curve developed in 9.6.4.4.

### 8.4.2 Determination of the gaseous components

#### 8.4.2.1 Introduction

The gaseous components emitted by the engine submitted for testing shall be measured by the methods described in 9.5. They shall be determined in the diluted exhaust gas. Data evaluation and calculation procedures are described in 8.4.2.3 and 8.4.2.4.

#### 8.4.2.2 Sampling for gaseous emissions

The exhaust pipe between the engine and the full flow dilution system shall conform to the requirements of 9.5.3.1.The gaseous emissions sample probe(s) shall be installed in the dilution tunnel at a point where the dilution air and exhaust gas are well mixed, and in close proximity to the particulates sampling probe.

Sampling can generally be done in two ways:

- the pollutants are sampled into a sampling bag over the cycle and measured after completion of the test; for HC, the sample bag must be heated to $464 \pm 11$ K ($191 \pm 11$ °C), for $NO_x$, the sample bag temperature must be above the dew point temperature;

- the pollutants are sampled continuously and integrated over the cycle.

The background concentrations shall be sampled upstream of the dilution tunnel into a sampling bag, and shall be subtracted from the emissions concentration according to 8.4.2.4.2.

#### 8.4.2.3 Data evaluation

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

#### 8.4.2.4 Calculation of mass emission

#### 8.4.2.4.1 Systems with constant mass flow

For systems with heat exchanger, the mass of the pollutants shall be determined from the following equation:

a) for the WHTC

$$m_{gas} = u_{gas} \times c_{gas} \times m_{ed} \qquad \text{(in g/test)} \qquad (45)$$

b) for each mode of the WHSC

$$m_{gas} = u_{gas} \times c_{gas} \times q_{dmew} \qquad \text{(in g/h)} \qquad (46)$$

where

| | | |
|---|---|---|
| $u_{gas}$ | = | ratio between density of exhaust component and density of air |
| $c_{gas}$ | = | average background corrected concentration of the respective component, ppm |
| $m_{ed}$ | = | total diluted exhaust mass over the cycle, kg |
| $q_{mdew}$ | = | diluted exhaust gas mass flow rate, kg/s |

For the calculation of $NO_x$, the humidity correction factor $k_{h,D}$, or $k_{h,G}$, as applicable, as determined according to 8.2 shall be used.

The measured concentration shall be converted to a wet basis according to 8.1, if not already measured on a wet basis

Values for $u$ are given in table 5 below for selected components:

**Table 5 — Values of $u$ in the diluted exhaust gas**

| Gas | | $NO_x$ | CO | HC | $CO_2$ | $O_2$ | $CH_4$ | HCHO | $CH_3OH$ |
|---|---|---|---|---|---|---|---|---|---|
| $r_{gas}$ [kg/m³] | | 2,053 | 1,250 | a) | 1,9636 | 1,4277 | 0,716 | 1,340 | 1,430 |
| **FUEL** | $r_{air}$ = 1,293 kg/m³ Coefficient $u_{gas}$ b) | | | | | | | | |
| Diesel | | 0,001588 | 0,000967 | 0,000480 | 0,001519 | 0,001104 | 0,000553 | 0,001036 | 0,001106 |
| RME | | 0,001588 | 0,000967 | 0,000537 | 0,001519 | 0,001104 | 0,000553 | 0,001036 | 0,001106 |
| Methanol | | 0,001588 | 0,000967 | 0,001105 | 0,001519 | 0,001104 | 0,000553 | 0,001036 | 0,001106 |
| Ethanol | | 0,001588 | 0,000967 | 0,000795 | 0,001519 | 0,001104 | 0,000553 | 0,001036 | 0,001106 |
| Natural Gas c) | | 0,001588 | 0,000967 | 0,000584 d) | 0,001519 | 0,001104 | 0,000553 | 0,001036 | 0,001106 |
| Propane | | 0,001588 | 0,000967 | 0,000507 | 0,001519 | 0,001104 | 0,000553 | 0,001036 | 0,001106 |
| Butane | | 0,001588 | 0,000967 | 0,000501 | 0,001519 | 0,001104 | 0,000553 | 0,001036 | 0,001106 |
| Gasoline | | 0,001588 | 0,000967 | 0,000483 | 0,001519 | 0,001104 | 0,000553 | 0,001036 | 0,001106 |

a)  depending on fuel
b)  at $l$ = 2, dry air, 273 K, 101,3 kPa
c)  $u$ accurate within 0,2 % for mass composition of: C = 66 - 76 %; H = 22 - 25 %; N = 0 - 12 %
d)  NMHC on the basis of $CH_{2,93}$ (for total HC the $u_{gas}$ coefficient of $CH_4$ shall be used)

NOTE    For calculating the $u_{gas}$ values, the density of the diluted exhaust gas has been assumed to be equal to air density. Therefore, the $u_{gas}$ values are identical for single gas components, but different for HC.

**8.4.2.4.2    Determination of the background corrected concentrations**

The average background concentration of the gaseous pollutants in the dilution air shall be subtracted from measured concentrations to get the net concentrations of the pollutants. The average values of the background concentrations can be determined by the sample bag method or by continuous measurement with integration. The following formula shall be used.

$$c = c_e - c_d \times (1 - (1/DF)) \qquad (46)$$

where

| | | |
|---|---|---|
| $c_e$ | = | concentration of the respective pollutant measured in the diluted exhaust gas, ppm |
| $c_d$ | = | concentration of the respective pollutant measured in the dilution air, ppm |
| $DF$ | = | dilution factor |

The dilution factor shall be calculated as follows:

a) for diesel and LPG fueled gas engines

$$DF = \frac{F_S}{CO2_{conce} + (HC_{conce} + CO_{conce}) * 10^{-4}}$$ (47)

b) for NG fueled gas engines

$$DF = \frac{F_S}{CO2_{conce} + (NMHC_{conce} + CO_{conce}) * 10^{-4}}$$ (48)

where

| | | |
|---|---|---|
| $CO_{2,conce}$ | = | concentration of $CO_2$ in the diluted exhaust gas, % vol |
| $HC_{conce}$ | = | concentration of HC in the diluted exhaust gas, ppm C1 |
| $NMHC_{conce}$ | = | concentration of NMHC in the diluted exhaust gas, ppm C1 |
| $CO_{conce}$ | = | concentration of CO in the diluted exhaust gas, ppm |
| $F_S$ | = | stoichiometric factor |

Concentrations measured on dry basis shall be converted to a wet basis in accordance with clause

The stoichiometric factor shall be calculated as follows:

$$F_S = 100 * \frac{x}{x + \frac{y}{2} + 3,76 * \left(x + \frac{y}{4}\right)}$$ (49)

where

x,y = fuel composition $C_xH_y$

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

| | | |
|---|---|---|
| $F_S$ (diesel) | = | 13,4 |
| $F_S$ (LPG) | = | 11,6 |
| $F_S$ (NG) | = | 9,5 |

### 8.4.2.4.3 Systems with Flow Compensation (WHTC only)

For systems without heat exchanger, the mass of the pollutants (g/test) shall be determined by calculating the instantaneous mass emissions and integrating the instantaneous values over the cycle. Also, the background correction shall be applied directly to the instantaneous concentration value. The following formulae shall be applied:

$$m_{gas} = \sum_{i=1}^{n} \left[ (m_{ed,i} \times c_e \times u_{gas}) \right] - \left[ (m_{ed} \times c_d \times (1 - 1/DF) \times u_{gas}) \right]$$ (50)

where

| | | |
|---|---|---|
| $c_e$ | = | concentration of the respective pollutant measured in the diluted exhaust gas, ppm |
| $c_d$ | = | concentration of the respective pollutant measured in the dilution air, ppm |
| $m_{ed,i}$ | = | instantaneous mass of the diluted exhaust gas, kg |
| $m_{ed}$ | = | total mass of diluted exhaust gas over the cycle, kg |
| $u_{gas}$ | = | tabulated value from table 5 |
| $DF$ | = | dilution factor |

### 8.4.2.4.4 Calculation of NMHC and CH$_4$ with the non-methane cutter

The concentration of NMHC and $CH_4$ shall be calculated as follows:

$$c_{NMHC} = \frac{c_{HC(w/oCutter)} \times (1 - E_M) - c_{HC(w/Cutter)}}{E_E - E_M}$$ (51)

$$c_{CH4} = \frac{c_{HC(w/Cutter)} - c_{HC(w/oCutter)} \times (1 - E_E)}{E_E - E_M}$$ (52)

where:

| $c_{HC(w/Cutter)}$ | = | HC concentration with the sample gas flowing through the NMC |
| $c_{HC(w/oCutter)}$ | = | HC concentration with the sample gas bypassing the NMC |
| $E_M$ | = | methane efficiency as determined per 9.3.3.11.1 |
| $E_E$ | = | ethane efficiency as determined per 9.3.3.11.2 |

### 8.4.2.5 Calculation of the specific emissions

The emissions (g/kWh) shall be calculated for all components in accordance with 8.3.2.6.

## 8.4.3 Particulate determination

### 8.4.3.1 Introduction

The determination of the particulates requires a dilution system. In this clause, dilution shall be accomplished by a full flow dilution system. The flow capacity of the dilution system shall be large enough to completely eliminate water condensation in the dilution and sampling systems, and maintain the temperature of the diluted exhaust gas between 315 K (42°C) and 325 K (52°C) immediately upstream of the filter holders. Dehumidifying the dilution air before entering the dilution system is permitted, and especially useful if dilution air humidity is high. The temperature of the dilution air shall be higher than 288 K (15°C) in close proximity to the entrance into the dilution tunnel.

To determine the mass of the particulates, a particulate sampling system, particulate sampling filters, a microgram balance, and a temperature and humidity controlled weighing chamber, are required. The details of the system are described in 9.4.

### 8.4.3.2 Particulate sampling

The particulate sampling probe shall be installed in close proximity to the gaseous emissions sampling probe, but sufficiently distant as to not cause interference, in the dilution tunnel. Therefore, the installation provisions of clause 8.3.2.2 also apply to particulate sampling. The sampling line shall conform to the requirements of 9.5.3.1.

### 8.4.3.3 Calculation of mass emission

The particulate mass (g/test) shall be calculated as follows:

$$m_{PM} = \frac{m_f}{m_{sep}} \times \frac{m_{ed}}{1000} \tag{53}$$

where

| $m_f$ | = | particulate mass sampled over the cycle, mg |
| $m_{sep}$ | = | mass of diluted exhaust gas passing the particulate collection filters, kg |
| $m_{ed}$ | = | mass of diluted exhaust gas over the cycle, kg |

If a double dilution system is used, the mass of the secondary dilution air shall be subtracted from the total mass of the double diluted exhaust gas sampled through the particulate filters.

$$m_{sep} = m_{set} - m_{ssd} \tag{54}$$

where

| $m_{set}$ | = | mass of double diluted exhaust gas through particulate filter, kg |
| $m_{ssd}$ | = | mass of secondary dilution air, kg |

If the particulate background level of the dilution air is determined in accordance with clause 7.7.5, the particulate mass may be background corrected. In this case, the particulate mass (g/test) shall be calculated as follows:

$$m_{PM} = \left[ \frac{m_f}{m_{sep}} - \left( \frac{m_b}{m_{sd}} \times \left( 1 - \frac{1}{DF} \right) \right) \right] \times \frac{m_{ed}}{1000} \tag{55}$$

where

| | | |
|---|---|---|
| $m_{PM}, m_{sep}, m_{ed}$ | = | see above |
| $m_{sd}$ | = | mass of primary dilution air sampled by background particulate sampler, kg $m_b$ |
| | = | mass of the collected background particulates of the primary dilution air, mg |
| $DF$ | = | dilution factor as determined in 8.4.2.4.2 |

### 8.4.3.4 Calculation of the specific emissions

The particulate emission (g/kWh) shall be calculated in accordance with 8.3.3.6.

### 8.4.3.5 Effective weighting factor (WHSC only)

For the WHSC, the effective weighting factor $W_{FEi}$, for each mode shall be calculated according to 8.3.3.7.

## 9 Measurement Equipment

### 9.1 Dynamometer specification

An engine dynamometer with adequate characteristics to perform the appropriate test cycle described in 7.2 and 7.3 shall be used.

The instrumentation for torque and speed measurement shall allow the measurement accuracy of the shaft power within the given limits. Additional calculations may be necessary. The accuracy of the measuring equipment must be such that the maximum tolerances of the figures given in 9.2 are not exceeded.

### 9.2 Accuracy

The equipment described in this standard shall be used for emissions tests of engines. This standard does not contain details of flow, pressure, and temperature measuring equipment. Instead, only the accuracy requirements of such equipment necessary for conducting an emissions test are given in this clause. The instruments shall be calibrated as required by internal audit procedures, by the instrument manufacturer or in accordance with ISO 9000 requirements.

The calibration of all measuring instruments shall be traceable to national (international) standards and comply with the requirements given in table 6:

**Table 6 — Permissible deviations of instruments**

| No. | Measurement instrument | Permissible deviation |
|---|---|---|
| 1 | Engine speed | $\pm$ 2 % of reading |
| 2 | Torque | $\pm$ 2 % of reading or $\pm$ 1 % of engine's max. value whichever is larger |
| 3 | Fuel consumption | $\pm$ 2 % of engine's max. value |
| 4 | Air consumption | $\pm$ 2 % of reading or $\pm$ 1 % of engine's max. value whichever is larger |
| 5 | Exhaust gas flow | $\pm$ 2,5 % of reading or $\pm$ 1,5 % of engine's max. value whichever is larger |
| 6 | Temperatures $\leq$ 600 K | $\pm$ 2 K absolute |
| 7 | Temperatures > 600 K | $\pm$ 1 % of reading |
| 8 | Exhaust gas pressure | $\pm$ 0,2 kPa absolute |
| 9 | Intake air depression | $\pm$ 0,05 kPa absolute |
| 10 | Atmospheric pressure | $\pm$ 0,1 kPa absolute |
| 11 | Other pressures | $\pm$ 0,1 kPa absolute |
| 12 | Absolute humidity | $\pm$ 5 % of reading |
| 13 | Dilution air flow | $\pm$ 2 % of reading |
| 14 | Diluted exhaust gas flow | $\pm$ 2 % of reading |

## 9.3     Gaseous Emissions Measurement and Sampling System

### 9.3.1     Analyzer specifications

**9.3.1.1          general**

The analyzers shall have a measuring range and response time appropriate for the accuracy required to measure the concentrations of the exhaust gas components under transient and steady state conditions. The analyzer range shall be selected such that the average concentration measured over the test cycle falls between 15 % and 100 % of full scale, except the accuracy of the analyzer does not exceed ± 2 % of reading for the average concentration.

If read-out systems (computers, data loggers) can provide sufficient accuracy and resolution below 15 % of full scale, measurements below 15 % of full scale are also acceptable. In this case, additional calibrations of at least 4 non-zero nominally equally spaced points are to be made to ensure the accuracy of the calibration curves according to clause 9.3.3.6.3.

The electromagnetic compatibility (EMC) of the equipment shall be on a level as to minimize additional errors.

**9.3.1.2          Accuracy**

The analyzer shall not deviate from the nominal calibration point by more than ± 2 % of the reading or ± 0,3 % of full scale whichever is larger. The accuracy shall be determined according to the calibration requirements laid down in clause 9.3.3.6.

NOTE     For the purpose of this standard, accuracy is defined as the deviation of the analyzer reading from the nominal calibration values using a calibration gas ($\equiv$ true value)

**9.3.1.3          Precision**

The precision, defined as 2,5 times the standard deviation of 10 repetitive responses to a given calibration or span gas, has to be not greater than 1 % of full scale concentration for each range used above 155 ppm (or ppmC) or 2% of each range used below 155 ppm (or ppmC).

**9.3.1.4          Noise**

The analyzer peak-to-peak response to zero and calibration or span gases over any 10 seconds period shall not exceed 2 % of full scale on all ranges used.

**9.3.1.5          Zero drift**

Zero response is defined as the mean response, including noise, to a zero gas during a 30 seconds time interval. The drift of the zero response during a one hour period shall be less than 2 % of full scale on the lowest range used.

**9.3.1.6          Span drift**

Span response is defined as the mean response, including noise, to a span gas during a 30 seconds time interval. The drift of the span response during a one hour period shall be less than 2 % of full scale on the lowest range used.

**9.3.1.7          Rise time**

The rise time of the analyzer installed in the measurement system shall not exceed 2,5 s.

NOTE     Only evaluating the response time of the analyzer alone will not clearly define the suitability of the total system for transient testing. Volumes and especially dead volumes through out the system will not only effect the transportation time from the probe to the analyzer, but also effect the rise time. Also transport times inside of an analyzer would be defined as analyzer response time, like the converter or water traps inside of a NOx analyzers. The determination of the total system response time is described in clause 9.3.3.5.

**9.3.1.8          Gas drying**

Exhaust gases may be measured wet or dry. A gas drying device, if used, shall have a minimal effect on the composition of the measured gases. Chemical dryers are not an acceptable method of removing water from the sample.

### 9.3.2 Analyzers

#### 9.3.2.1 Introduction

9.3.2.2 to 9.2.3.7 describe the measurement principles to be used. A detailed description of the measurement systems is given in 9.3.4. The gases to be measured shall be analyzed with the following instruments. For non-linear analyzers, the use of linearizing circuits is permitted.

#### 9.3.2.2 Carbon monoxide (CO) analysis

The carbon monoxide analyzer shall be of the non-dispersive infrared (NDIR) absorption type.

#### 9.3.2.3 Carbon dioxide ($CO_2$) analysis

The carbon dioxide analyzer shall be of the non-dispersive infrared (NDIR) absorption type.

#### 9.3.2.4 Hydrocarbon (HC) analysis

The hydrocarbon analyzer shall be of the heated flame ionization detector (HFID) type with detector, valves, pipework, etc. heated so as to maintain a gas temperature of 463K ± 10K (190 ± 10°C). Optionally, for NG fueled and SI engines, the hydrocarbon analyzer may be of the non heated flame ionization detector (FID) type depending upon the method used (see 9.3.4.3).

#### 9.3.2.5 Non-methane hydrocarbon (NMHC) analysis

The determination of the non-methane hydrocarbon fraction shall be performed with a heated non-methane cutter (NMC) operated in line with an FID as per 9.3.4.4 by subtraction of the methane from the hydrocarbons.

#### 9.3.2.6 Oxides of nitrogen ($NO_x$) analysis

If measured on a dry basis, the oxides of nitrogen analyzer shall be of the chemiluminescent detector (CLD) or heated chemiluminescent detector (HCLD) type with a $NO_2$/NO converter. If measured on a wet basis, a HCLD with converter maintained above 328 K (55°C) shall be used, provided the water quench check (see 9.3.3.12) is satisfied. For both CLD and HCLD, the sampling path shall be maintained at a wall temperature of 328 K to 473 K (55°C to 200°C) up to the converter for dry measurement, and up to the analyzer for wet measurement.

#### 9.3.2.7 Air to fuel measurement

The air to fuel measurement equipment used to determine the exhaust gas flow as specified in 8.3.1.6 shall be a wide range air to fuel ratio sensor or lambda sensor of Zirconia type.

The sensor shall be mounted directly on the exhaust pipe where the exhaust gas temperature is high enough to eliminate water condensation.

The accuracy of the sensor with incorporated electronics shall be within:
± 3 % of reading       $\lambda < 2$
± 5 % of reading      $2 \leq \lambda < 5$
± 10 % of reading     $5 \leq \lambda$

To fulfill the accuracy specified above, the sensor shall be calibrated as specified by the instrument manufacturer.

### 9.3.3 Calibration

#### 9.3.3.1 Introduction

Each analyzer shall be calibrated as often as necessary to fulfill the accuracy requirements of this Regulation. The calibration method that shall be used is described in this section for the analyzers indicated in 9.3.2 and 9.3.4.

#### 9.3.3.2 Calibration gases

The shelf life of all calibration gases shall be respected. The expiration date of the calibration gases stated by the manufacturer shall be recorded.

#### 9.3.3.2.1 Pure gases

The required purity of the gases is defined by the contamination limits given below. The following gases shall be available for operation:

      Purified nitrogen

(Contamination $\leq$ 1 ppm C1, $\leq$1 ppm CO, $\leq$ 400 ppm $CO_2$, $\leq$ 0,1 ppm NO)

Purified oxygen
(Purity > 99.5 % vol $O_2$)

Hydrogen-helium mixture
(40 $\pm$ 2% hydrogen, balance helium)
(Contamination $\leq$ 1 ppm C1, $\leq$ 400 ppm $CO_2$)

Purified synthetic air
(Contamination $\leq$ 1 ppm C1, $\leq$ 1 ppm CO, $\leq$ 400 ppm $CO_2$, $\leq$ 0,1 ppm NO)
(Oxygen content between 18-21 % vol.)

### 9.3.3.2.2        Calibration and span gases

Mixtures of gases having the following chemical compositions shall be available:

$C_3H_8$ and purified synthetic air (see 9.3.3.2.1);

CO and purified nitrogen;

$NO_x$ and purified nitrogen (the amount of $NO_2$ contained in this calibration gas shall not exceed 5 % of the NO content);

$CO_2$ and purified nitrogen

$CH_4$ and purified synthetic air

$C_2H_6$ and purified synthetic air

NOTE        Other gas combinations are allowed provided the gases do not react with one another.

The true concentration of a calibration and span gas shall be within $\pm$ 1 % of the nominal value, and shall be traceable to national and international standards. All concentrations of calibration gas shall be given on a volume basis (volume percent or volume ppm).

### 9.3.3.2.3        Use of precision blending devices

The gases used for calibration and span may also be obtained by means of precision blending devices (gas dividers), diluting with purified $N_2$ or with purified synthetic air. The accuracy of the mixing device shall be such that the concentration of the blended calibration gases  is accurate to within $\pm$ 2 %. This accuracy implies that primary gases used for blending shall be known to an accuracy of at least $\pm$ 1 %, traceable to national or international gas standards. The verification shall be performed at between 15 and 50 % of full scale for each calibration incorporating a blending device. An additional verification may be performed using another calibration gas, if the first verification has failed.

Optionally, the blending device may be checked with an instrument which by nature is linear, e.g. using NO gas with a CLD. The span value of the instrument shall be adjusted with the span gas directly connected to the instrument. The blending device shall be checked at the used settings and the nominal value shall be compared to the measured concentration of the instrument. This difference shall in each point be within $\pm$ 1% of the nominal value.

Other methods may be used based on good engineering practice and with the prior agreement of the parties involved.

NOTE        The precision gas divider whose accuracy is within $\pm$ 1 %, is recommended to establish the accurate analyzer calibration curve. The gas divider shall be calibrated by the instrument manufacture in accordance with ISO 9000 requirements.

### 9.3.3.2.4        Oxygen interference check gases

Oxygen interference check gases are a blend of propane, oxygen and nitrogen. They shall contain propane with 350 ppmC $\pm$ 75 ppmC hydrocarbon. The concentration value shall be determined to calibration gas tolerances by chromatographic analysis of total hydrocarbons plus impurities or by dynamic blending. The oxygen concentrations required for gasoline and diesel engine testing are listed in table 7 with the remainder being purified nitrogen:

**Table 7 — Oxygen interference check gases**

| Type of engine | $O_2$ concentration [%] |
|---|---|
| Diesel | 21 (20 to 22) |
| Diesel and gasoline | 10 (9 to 11) |
| Diesel and gasoline | 5 (4 to 6) |
| Gasoline | 0 (0 to 1) |

### 9.3.3.3 Operating procedure

The operating procedure for analyzers shall follow the start-up and operating instructions of the instrument manufacturer. The minimum requirements given in clauses 9.3.3.4 to 9.3.3.9 shall be included.

### 9.3.3.4 Leakage test

A system leakage test shall be performed. The probe shall be disconnected from the exhaust system and the end plugged. The analyzer pump shall be switched on. After an initial stabilization period all flow meters should read zero. If not, the sampling lines shall be checked and the fault corrected.

The maximum allowable leakage rate on the vacuum side shall be 0,5% of the in-use flow rate for the portion of the system being checked. The analyzer flows and bypass flows may be used to estimate the in-use flow rates.

Alternatively, the system may be evacuated to a pressure of at least 20 kPa vacuum (80 kPa absolute). After an initial stabilisation period the pressure increase $Dp$ (kPa/min) in the system should not exceed:

$$Dp = p / V_s \times 0,005 \times q_{vs} \tag{56}$$

where:

$V_s$     =     system volume, l

$q_{vs}$     =     system flow rate, l/min

Another method is the introduction of a concentration step change at the beginning of the sampling line by switching from zero to span gas. If after an adequate period of time the reading is about 1 % low compared to the introduced concentration, this points to calibration or leakage problems.

### 9.3.3.5 Response time check of the analytical system

The system settings for the response time evaluation shall be exactly the same as during measurement of the test run (i.e. pressure, flow rates, filter settings on the analyzers and all other response time influences). The response time determination shall be done with gas switching directly at the inlet of the sample probe. The gas switching shall be done in less than 0,1 second. The gases used for the test shall cause a concentration change of at least 60% FS.

The concentration trace of each single gas component shall be recorded. The response time is defined to be the difference in time between the gas switching and the appropriate change of the recorded concentration. The system response time ($t_{90}$) consists of the delay time to the measuring detector and the rise time of the detector. The delay time is defined as the time from the change ($t_0$) until the response is 10% of the final reading ($t_{10}$). The rise time is defined as the time between 10% and 90% response of the final reading ($t_{90} - t_{10}$).

For time alignment of the analyzer and exhaust flow signals, the transformation time is defined as the time from the change ($t_0$) until the response is 50% of the final reading ($t_{50}$).

The system response time shall be ≤ 10 seconds with a rise time ≤ 2,5 seconds in accordance with 9.3.1.7 for all limited components (CO, NOx, HC or NMHC) and all ranges used.

### 9.3.3.6 Calibration procedure

#### 9.3.3.6.1 Instrument assembly

The instrument assembly shall be calibrated and calibration curves checked against standard gases. The same gas flow rates shall be used as when sampling exhaust.

#### 9.3.3.6.2 Warming-up time

The warming-up time should be according to the recommendations of the manufacturer. If not specified, a

minimum of two hours is recommended for warming up the analyzers.

### 9.3.3.6.3 Establishment of the calibration curve

a) Each normally used operating range shall be calibrated.

b) Using purified synthetic air (or nitrogen), the CO, $CO_2$, $NO_x$ and HC analyzers shall be set at zero.

c) The appropriate calibration gases shall be introduced to the analyzers, the values recorded, and the calibration curve established.

d) The calibration curve shall be established by at least 6 calibration points (excluding zero) approximately equally spaced over the operating range. The highest nominal concentration shall be equal to or higher than 90 % of full scale.

e) The calibration curve shall be calculated by the method of least-squares. A best-fit linear or non-linear equation may be used.

f) The calibration points shall not differ from the least-squares best-fit line by more than $\pm$ 2 % of reading or $\pm$ 0,3 % of full scale whichever is larger.

g) The zero setting shall be rechecked and the calibration procedure repeated, if necessary.

### 9.3.3.6.4 Alternative methods

If it can be shown that alternative technology (e.g. computer, electronically controlled range switch, etc.) can give equivalent accuracy, then these alternatives may be used.

### 9.3.3.7 Verification of the calibration curve

Each normally used operating range shall be checked prior to each engine test in accordance with the following procedure.

The calibration shall be checked by using a zero gas and a span gas whose nominal value is more than 80 % of full scale of the measuring range.

If, for the two points considered, the value found does not differ by more than $\pm$ 4 % of full scale from the declared reference value, the adjustment parameters may be modified. Should this not be the case, the span gas shall be verified or a new calibration curve shall be established in accordance with 9.3.3.6.3.

### 9.3.3.8 Calibration of tracer gas analyzer for exhaust flow measurement

The analyzer for measurement of the tracer gas concentration shall be calibrated using the standard gas.

The calibration curve shall be established by at least 10 calibration points (excluding zero) spaced so that a half of the calibration points are placed between 4% to 20% of analyzer's full scale and the rest are in between 20% to 100% of the full scale. The calibration curve is calculated by the method of least squares.

The calibration curve shall not differ by more than $\pm$ 1% of the full scale from the nominal value of each calibration point, in the range from 20% to 100% of the full scale. It also shall not differ by more than $\pm$ 2% of reading from the nominal value in the range from 4% to 20% of the full scale.

The analyzer shall be set at zero and spanned prior to the test run using a zero gas and a span gas whose nominal value is more than 80% of the analyzer full scale.

### 9.3.3.9 Efficiency test of $NO_x$ converter

The efficiency of the converter used for the conversion of $NO_2$ into NO is tested as given in 9.3.3.9.1 to 9.3.3.9.8 (see figure 5).

### 9.3.3.9.1 Test setup

Using the test setup as schematically shown in figure 5 and the procedure below, the efficiency of converters shall be tested by means of an ozonator.
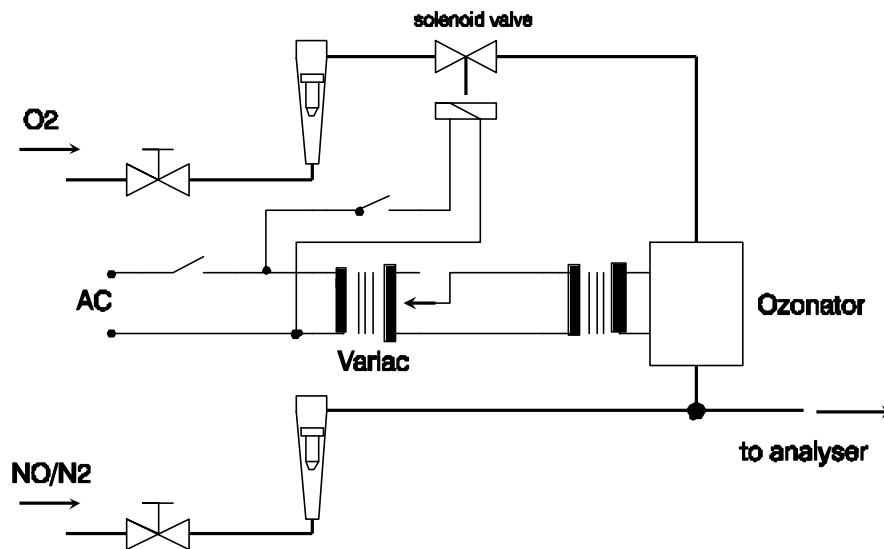
**Figure 5 – Schematic of NO₂ converter efficiency device**

**9.3.3.9.2          Calibration**

The CLD and the HCLD shall be calibrated in the most common operating range following the manufacturer's specifications using zero and span gas (the NO content of which shall amount to about 80 % of the operating range and the NO₂ concentration of the gas mixture to less than 5 % of the NO concentration). The NOₓ analyzer shall be in the NO mode so that the span gas does not pass through the converter. The indicated concentration has to be recorded.

**9.3.3.9.3          Calculation**

The % efficiency of the NOx converter is calculated as follows:

$$E_{\mathrm{NOx}} = \left(1 + \frac{a - b}{c - d}\right) \times 100$$

(57

where

$a$ is the NOₓ concentration according to 9.3.3.9.6;

$b$ is the NOₓ concentration according to 9.3.3.9.7;

$c$ is the NO concentration according to 9.3.3.9.4;

$d$ is the NO concentration according to 9.3.3.9.5;

**9.3.3.9.4          Adding of oxygen**

Via a T-fitting, oxygen or zero air is added continuously to the gas flow until the concentration indicated is about 20 % less than the indicated calibration concentration given in 9.3.3.9.2. (The analyzer is in the NO mode).

The indicated concentration (c) shall be recorded. The ozonator is kept deactivated throughout the process.

**9.3.3.9.5          Activation of the ozonator**

The ozonator is now activated to generate enough ozone to bring the NO concentration down to about 20 % (minimum 10 %) of the calibration concentration given in 9.3.3.9.2. The indicated concentration (d) shall be recorded (The analyzer is in the NO mode).

**9.3.3.9.6          NOx mode**

The NO analyzer is then switched to the NOₓ mode so that the gas mixture (consisting of NO, NO₂, O₂ and N₂) now passes through the converter. The indicated concentration (a) shall be recorded. (The analyzer is in the NOₓ mode).

#### 9.3.3.9.7 Deactivation of the ozonator

The ozonator is now deactivated. The mixture of gases described in 9.3.3.9.6 passes through the converter into the detector. The indicated concentration (b) shall be recorded. (The analyzer is in the $NO_x$ mode).

#### 9.3.3.9.8 NO mode

Switched to NO mode with the ozonator deactivated, the flow of oxygen or synthetic air is also shut off. The $NO_x$ reading of the analyzer shall not deviate by more than ± 5 % from the value measured according to 9.3.3.9.2. (The analyzer is in the NO mode).

#### 9.3.3.9.9 Test interval

The efficiency of the converter shall be tested prior to each calibration of the $NO_x$ analyzer.

#### 9.3.3.9.10 Efficiency requirement

The efficiency of the converter $E_{NOx}$ shall not be less than 90 %, but a higher efficiency of 95 % is strongly recommended.

If, with the analyzer in the most common range, the ozonator cannot give a reduction from 80 % to 20 % according to 9.3.3.9.5, then the highest range which will give the reduction shall be used.

#### 9.3.3.10 Adjustment of the FID

#### 9.3.3.10.1 Optimization of the detector response

The FID shall be adjusted as specified by the instrument manufacturer. A propane in air span gas should be used to optimize the response on the most common operating range.

With the fuel and air flow rates set at the manufacturer's recommendations, a 350 ± 75 ppmC span gas shall be introduced to the analyzer. The response at a given fuel flow shall be determined from the difference between the span gas response and the zero gas response. The fuel flow shall be incrementally adjusted above and below the manufacturer`s specification. The span and zero response at these fuel flows shall be recorded. The difference between the span and zero response shall be plotted and the fuel flow adjusted to the rich side of the curve. This is the initial flow rate setting which may need further optimization depending on the results of the hydrocarbon response factors and the oxygen interference check according to clauses 9.3.3.10.2 and 9.3.3.10.3.

If the oxygen interference or the hydrocarbon response factors do not meet the following specifications, the air flow shall be incrementally adjusted above and below the manufacturer's specifications, repeating clause 9.3.3.10.2 and clause 9.3.3.10.3 for each flow.

The optimization may optionally be conducted using the procedures outlined in SAE paper n° 770141.

#### 9.3.3.10.2 Hydrocarbon response factors

The analyzer shall be calibrated using propane in air and purified synthetic air, according to clause 9.3.3.6.

Response factors shall be determined when introducing an analyzer into service and after major service intervals. The response factor ($r_h$) for a particular hydrocarbon species is the ratio of the FID C1 reading to the gas concentration in the cylinder expressed by ppmC1.

The concentration of the test gas shall be at a level to give a response of approximately 80 % of full scale. The concentration shall be known to an accuracy of ± 2 % in reference to a gravimetric standard expressed in volume. In addition, the gas cylinder shall be preconditioned for 24 hours at a temperature of 298 K ± 5 K (25 °C ± 5 °C).

The test gases to be used and the recommended relative response factor ranges are as follows:

— Methane and purified synthetic air $\quad 1,00 \le r_h \le 1,15$

— Propylene and purified synthetic air $\quad 0,90 \le r_h \le 1,1$

— Toluene and purified synthetic air $\quad 0,90 \le r_h \le 1,1$

These values are relative to a $r_h$ of 1 for propane and purified synthetic air.

#### 9.3.3.10.3 Oxygen interference check

The oxygen interference check shall be determined when introducing an analyzer into service and after major service intervals.

NOTE    The oxygen interference check need only be conducted if the measurement is done in the raw exhaust

gas.

A range shall be chosen where the oxygen interference check gases (see 9.3.3.2.4) will fall in the upper 50 %. The test shall be conducted with the oven temperature set as required. Oxygen interference check gas specifications are found in 9.3.3.2.4.

a) The analyzer shall be set at zero.

b) The analyzer shall be spanned with the 0 % oxygen blend for gasoline-fueled engines. Diesel engine instruments shall be spanned with the 21 % oxygen blend.

c) The zero response shall be rechecked. If it has changed by more than 0,5 % of full scale, steps a) and b) of this clause shall be repeated.

d) The 5 % and 10 % oxygen interference check gases shall be introduced.

e) The zero response shall be rechecked. If it has changed by more than $\pm$ 1 % of full scale, the test shall be repeated.

f) The oxygen interference $(\%O_2I)$ shall be calculated for each mixture in step d) as follows:

$$\%O_2I = (B \text{ - Analyzer Response}) \times 100 / B \tag{58}$$

$$\text{Analyzer response} = (A / \% \text{ FS at } A) \times (\% \text{ FS at } B) \tag{59}$$

where
$A$ = hydrocarbon concentration the span gas used in step b), ppmC
$B$ = hydrocarbon concentration of the oxygen interference check gases used in step d), ppm C

g) The oxygen interference $(\%O_2I)$ shall be less than $\pm$ 3.0 % for all required oxygen interference check gases prior to testing.

h) If the oxygen interference is greater than $\pm$ 3.0 %, the air flow above and below the manufacturer's specifications shall be incrementally adjusted, repeating 9.3.3.10.1 for each flow.

l) If the oxygen interference is greater than $\pm$ 3.0 % after adjusting the air flow, the fuel flow and thereafter the sample flow shall be varied, repeating 9.3.3.10.1 for each new setting.

k) If the oxygen interference is still greater than $\pm$ 3.0 %, the analyzer, FID fuel, or burner air shall be repaired or replaced prior to testing. This clause shall then be repeated with the repaired or replaced equipment or gases.

**9.3.3.10.4        Methanol response factor**

When the FID analyzer is to be used for the analysis of hydrocarbons containing methanol, the methanol response factor ($r_m$) of the analyzer shall be established.

A known volume of methanol ($a$ in millilitres) is injected, using a microlitre syringe, into the heated mixing zone (395 K (122°C)) of a septum injector, vaporized and swept into a tedlar bag with a known volume of zero-grade air ($b$ in m³). The air volume(s) shall be such that the methanol concentration in the bag is representative of the range of concentrations found in the exhaust sample.

The bag sample is analyzed using the FID, and the response factor $r_m$ is calculated as follows:

$$r_m = \frac{FID}{SAM} \tag{60}$$

where

$FID$    =    FID reading, ppmC
$SAM$    =    Methanol concentration in the sample bag, as calculated from $a$ and $b$: $SAM = 594 \times a/b$, ppmC

**9.3.3.11        Efficiency of the Non-Methane Cutter (NMC)**

The NMC is used for the removal of the non-methane hydrocarbons from the sample gas by oxidizing all hydrocarbons except methane. Ideally, the conversion for methane is 0 %, and for the other hydrocarbons represented by ethane is 100 %. For the accurate measurement of NMHC, the two efficiencies shall be determined and used for the calculation of the NMHC emission mass flow rate (see 8.3.2.5).

#### 9.3.3.11.1 Methane Efficiency

Methane calibration gas shall be flown through the FID with and without bypassing the NMC and the two concentrations recorded. The efficiency shall be determined as follows:

$$E_M = 1 - \frac{c_{HC(w/cutter)}}{c_{HC(w/o\ cutter)}} \qquad\qquad (61)$$

where

$c_{HC(w/cutter)}$ = HC concentration with $CH_4$ flowing through the NMC, ppmC

$c_{HC(w/o\ cutter)}$ = HC concentration with $CH_4$ bypassing the NMC, ppmC

#### 9.3.3.11.2 Ethane Efficiency

Ethane calibration gas shall be flown through the FID with and without bypassing the NMC and the two concentrations recorded. The efficiency shall be determined as follows:

$$E_E = 1 - \frac{c_{HC(w/cutter)}}{c_{HC(w/o\ cutter)}} \qquad\qquad (62)$$

where

$c_{HC(w/cutter)}$ = HC concentration with $C_2H_6$ flowing through the NMC, ppmC

$c_{HC(w/o\ cutter)}$ = HC concentration with $C_2H_6$ bypassing the NMC, ppmC

#### 9.3.3.12 Interference effects

Other gases than the one being analyzed can interfere with the reading in several ways. Positive interference occurs in NDIR and PMD instruments where the interfering gas gives the same effect as the gas being measured, but to a lesser degree. Negative interference occurs in NDIR instruments by the interfering gas broadening the absorption band of the measured gas, and in CLD instruments by the interfering gas quenching the reaction. The interference checks in 9.3.3.12.1 and 9.3.3.12.2 shall be performed prior to an analyzer's initial use and after major service intervals.

#### 9.3.3.12.1 CO analyzer interference check

Water and $CO_2$ can interfere with the CO analyzer performance. Therefore, a $CO_2$ span gas having a concentration of 80 to 100 % of full scale of the maximum operating range used during testing shall be bubbled through water at room temperature and the analyzer response recorded. The analyzer response shall not be more than 1 % of full scale for ranges equal to or above 300 ppm or more than 3 ppm for ranges below 300 ppm.

#### 9.3.3.12.2 $NO_x$ analyzer quench checks

The two gases of concern for CLD (and HCLD) analyzers are $CO_2$ and water vapor. Quench responses to these gases are proportional to their concentrations, and therefore require test techniques to determine the quench at the highest expected concentrations experienced during testing.

##### 9.3.3.12.2.1 $CO_2$ quench check

A $CO_2$ span gas having a concentration of 80 to 100 % of full scale of the maximum operating range shall be passed through the NDIR analyzer and the $CO_2$ value recorded as $A$. It shall then be diluted approximately 50 % with NO span gas and passed through the NDIR and CLD, with the $CO_2$ and NO values recorded as $B$ and $C$, respectively. The $CO_2$ shall then be shut off and only the NO span gas be passed through the (H)CLD and the NO value recorded as $D$.

The % quench shall be calculated as follows:

$$E_{CO2} = \left[ 1 - \left( \frac{(C \times A)}{(D \times A) - (D \times B)} \right) \right] \times 100 \qquad\qquad (63$$

where

$A$ = undiluted $CO_2$ concentration measured with NDIR, %
$B$ = diluted $CO_2$ concentration measured with NDIR, %
$C$ = diluted NO concentration measured with (H)CLD, ppm
$D$ = undiluted NO concentration measured with (H)CLD, ppm

Alternative methods of diluting and quantifying of $CO_2$ and NO span gas values such as dynamic

mixing/blending, can be used.

*9.3.3.12.2.2          Water quench check*

This check applies to wet gas concentration measurements only. Calculation of water quench shall consider dilution of the NO span gas with water vapor and scaling of water vapor concentration of the mixture to that expected during testing.

A NO span gas having a concentration of 80 % to 100 % of full scale of the normal operating range shall be passed through the (H)CLD and  the NO value recorded as $D$. The NO span gas shall then be bubbled through water at room temperature and passed through the (H)CLD and the NO value recorded as $C$. The water temperature shall be determined and recorded as $F$. The mixture's saturation vapor pressure that corresponds to the bubbler water temperature ($F$) shall be determined and recorded as $G$. The water vapor concentration (in %) of the mixture shall be calculated as follows:

$$H = 100 \times (G / p_b)$$

(64)

and recorded as $H$. The expected diluted NO span gas (in water vapour) concentration shall be calculated as follows:

$$D_e = D \times ( 1 - H / 100 )$$

(65)

and recorded as $D_e$. For diesel exhaust, the maximum exhaust water vapor concentration (in %) expected during testing shall be estimated, under the assumption of a fuel H/C ratio of 1,8/1, from the maximum $CO_2$ concentration in the exhaust gas $A$ as follows:

$$H_m = 0,9 \times A$$

(66)

and recorded as $H_m$.

The % water quench shall be calculated as follows:

$$E_{H2O} = 100 \times ( ( D_e - C ) / D_e) \times (H_m / H) \qquad (67)$$

where

| | | |
|---|---|---|
| $D_e$ | = | expected diluted NO concentration, ppm |
| $C$ | = | measured diluted NO concentration, ppm |
| $H_m$ | = | maximum water vapour concentration, % |
| $H$ | = | actual water vapour concentration, % |

NOTE        It is important that the NO span gas contains minimal $NO_2$ concentration for this check, since absorption of $NO_2$ in water has not been accounted for in the quench calculations.

*9.3.3.12.2.3          Maximum allowable quench*

The quench shall not be greater than:

- For all dry CLD analysers it must be demonstrated that for the highest expected water vapor concentration (i. e. "%H2Oexp" as calculated later in this section), the water removal technique maintains CLD humidity at less or equal to 5 gwater/kgdry air (or about 0.008 percent H2O), which is 100 % RH at 3.9 °C and 101.3 kPa. This humidity specification is also equivalent to about 25 % RH at 25 °C and 101.3 kPa. This may be demonstrated by measuring the temperature at the outlet of a thermal dehumidifier, or by measuring humidity at a point just upstream of the CLD. Humidity of the CLD exhaust might also be measured as long as the only flow into the CLD is the flow of the dehumidifier.
- For raw measurement, $CO_2$-quench according to 9.3.3.12.2.1: 2 % of full scale
- For raw measurement, water quench according to 9.3.3.12.2.2: 3 % of full scale
- For dilute measurement: 2 % combined $CO_2$ and water quench

## 9.3.3.13          Calibration intervals

The analyzers shall be calibrated according to clause 9.3.3.6 at least every 3 months or whenever a system repair or change is made that could influence calibration.

### 9.3.4  Analytical system

#### 9.3.4.1          Introduction

Clause 9.3.4.2 and figures 6 and 7 contain general descriptions of the recommended sampling and analyzing systems. Since various configurations can produce equivalent results, exact conformance with figure 6 is not required. Components such as instruments, valves, solenoids, pumps, flow devices and switches may be used to provide additional information and coordinate the functions of the component systems. Other components which are not needed to maintain the accuracy on some systems, may be excluded if their exclusion is based upon good engineering judgement.

#### 9.3.4.2          Description of the analytical system

Analytical system for the determination of the gaseous emissions in the raw exhaust gas (figure 6) or in the diluted exhaust gas (figure 7) are described based on the use of:

- HFID or FID analyzer for the measurement of hydrocarbons;

- NDIR analyzers for the measurement of carbon monoxide and carbon dioxide;

- HCLD or CLD analyzer for the measurement of the oxides of nitrogen;

The sample for all components should be taken with one sampling probe and internally split to the different analyzers. Optionally, two sampling probes located in close proximity may be used. Care must be taken that no unintended condensation of exhaust components (including water and sulfuric acid) occurs at any point of the analytical system.
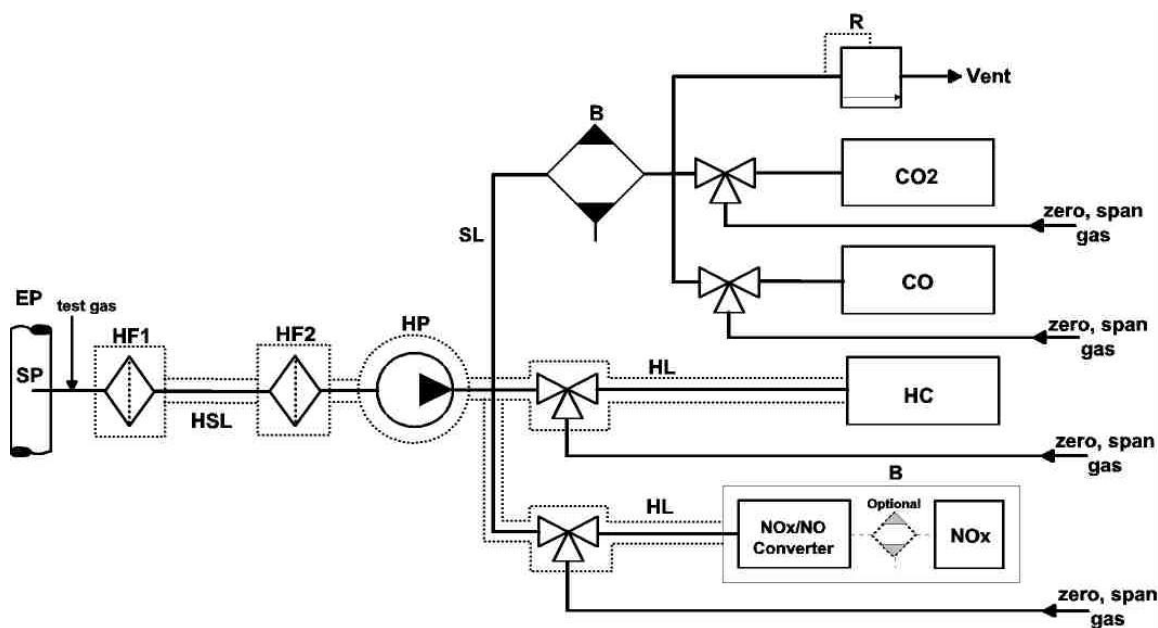


**Figure 6 — Schematic flow diagram of raw exhaust gas analysis system for CO, CO$_2$, NO$_x$, HC**
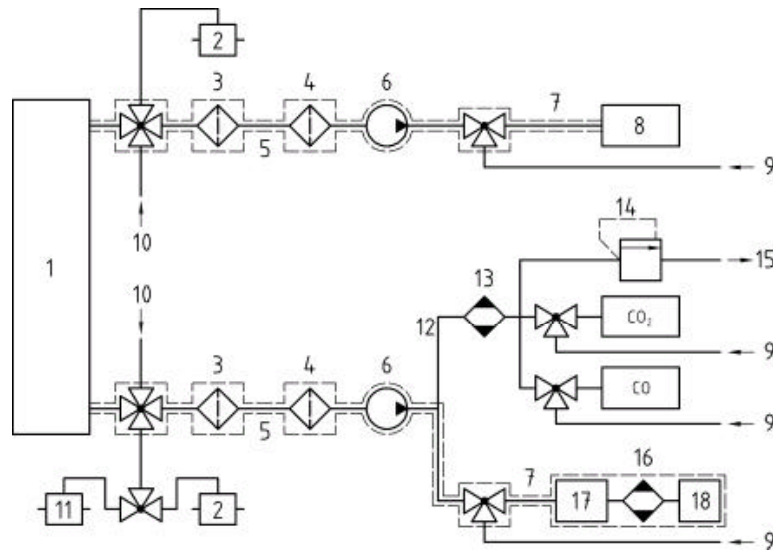
| 1 | DT | 4 | HF2 | 7 | HL | 10 | test gas | 13 | B | 16 | B |
|---|----|---|-----|---|-----|-----|----------|-----|---|-----|---|
| 2 | BK | 5 | HSL | 8 | HC | 11 | BG | 14 | R | 17 | $NO_x$/NO Converter |
| 3 | HF1 | 6 | HP | 9 | zero, span gas | 12 | SL | 15 | vent | 18 | $NO_x$ |

**Figure 7 — Schematic flow diagram of diluted exhaust gas analysis system for CO, $CO_2$, $NO_x$, HC**

### 9.3.4.3 Components of figures 6 and 7

**EP** **Exhaust pipe**

**SP** **Raw exhaust gas sampling probe (figure 6 only)**

A stainless steel straight closed end multi-hole probe is recommended. The inside diameter shall not be greater than the inside diameter of the sampling line. The wall thickness of the probe shall not be greater than 1 mm. There shall be a minimum of 3 holes in 3 different radial planes sized to sample approximately the same flow. The probe shall extend across at least 80 % of the diameter of the exhaust pipe. One or two sampling probes may be used.

**SP2** **Dilute exhaust gas HC sampling probe (figure 7 only)**

The probe shall:

— be defined as the first 254 mm to 762 mm of the heated sampling line HSL1;

— have a 5 mm minimum inside diameter;

— be installed in the dilution tunnel DT (see 9.5.3, figure 20) at a point where the dilution air and exhaust gas are well mixed (i.e. approximately 10 tunnel diameters downstream of the point where the exhaust enters the dilution tunnel);

— be sufficiently distant (radially) from other probes and the tunnel wall so as to be free from the influence of any wakes or eddies;

— be heated so as to increase the gas stream temperature to 463 K ± 10 K (190 °C ± 10 °C) at the exit of the probe, or to 385 K ± 10 K (112 °C ± 10 °C) for methanol-fuelled engines;

— non-heated in case of FID measurement (cold).

**SP3      Dilute exhaust gas CO, CO$_2$, NO$_x$ sampling probe (figure 7 only)**

The probe shall:

—        be in the same plane as SP2;

—        be sufficiently distant (radially) from other probes and the tunnel wall so as to be free from the influence of any wakes or eddies;

—        be heated and insulated over its entire length to a minimum temperature of 328 K (55 °C) to prevent water condensation.

**HF1      Heated pre-filter (optional)**

The temperature shall be the same as HSL.

**HF2      Heated filter**

The filter shall extract any solid particles from the gas sample prior to the analyzer. The temperature shall be the same as HSL. The filter shall be changed as needed.

**HSL      Heated sampling line**

The sampling line provides a gas sample from a single probe to the split point(s) and the HC analyzer.

The sampling line shall:

-    have a 4 mm minimum and a 13,5 mm maximum inside diameter;

-    be made of stainless steel or PTFE.

-    maintain a wall temperature of 463 K ± 10 K (190°C ± 10°C) as measured at every separately controlled heated section, if the temperature of the exhaust gas at the sampling probe is equal to or below 463 K (190°C);

-    maintain a wall temperature greater than 453 K (180°C), if the temperature of the exhaust gas at the sampling probe is above 463 K (190°C);

-    maintain a gas temperature of 463 K ± 10 K (190°C ± 10°C) immediately before the heated filter HF2 and the HFID;

**HL      Heated NO$_x$ sampling line**

The sampling line shall:

-    maintain a wall temperature of 328 K to 473 K (55°C to 200°C), up to the converter for dry measurement, and up to the analyzer for wet measurement.

-    be made of stainless steel or PTFE.

**HP      Heated sampling pump**

The pump shall be heated to the temperature of HSL.

**SL      Sampling line for CO and CO$_2$**

The line shall be made of PTFE or stainless steel. It may be heated or unheated.

**HC      HFID analyzer**

Heated flame ionization detector (HFID) or flame ionization detector (FID) for the determination of the hydrocarbons. The temperature of the HFID shall be kept at 453 K to 473 K (180°C to 200°C).

**CO, CO$_2$  NDIR analyzer**

NDIR analyzers for the determination of carbon monoxide and carbon dioxide (optional for the determination of the dilution ratio for PT measurement).

**NO$_x$      CLD analyzer**

CLD or HCLD analyzer for the determination of the oxides of nitrogen. If a HCLD is used it shall be kept at a temperature of 328 K to 473 K (55°C to 200°C).

**B**                               **Cooling bath (optional for NO measurement)**

To cool and condense water from the exhaust sample. It is optional if the analyzer is free from water vapor interference as determined in 9.3.3.12.2.2. If water is removed by condensation, the sample gas temperature or dew point shall be monitored either within the water trap or downstream. The sample gas temperature or dew point shall not exceed 280 K (7°C). Chemical dryers are not allowed for removing water from the sample.

**BK**         **Background bag (optional; figure 7 only)**

For the measurement of the background concentrations.

**BG**         **Sample bag (optional; figure 7 only)**

For the measurement of the sample concentrations.

**R**                               **Pressure regulator**

To control the pressure in the sampling lines and the flow to the analyzers.

**9.3.4.4**         **Non-methane cutter method (NMC)**

**9.3.4.4.1**         **General description**

The cutter oxidizes all hydrocarbons except $CH_4$ to $CO_2$ and $H_2O$, so that by passing the sample through the NMC only $CH_4$ is detected by the HFID. In addition to the usual HC sampling train (see 9.3.4.2, figures 6 and 7), a second HC sampling train shall be installed equipped with a cutter as laid out in figure 8. This allows simultaneous measurement of total HC and NMHC.

The cutter shall be characterized at or above 600 K (327°C) prior to test work with respect to its catalytic effect on $CH_4$ and $C_2H_6$ at $H_2O$ values representative of exhaust stream conditions. The dewpoint and $O_2$ level of the sampled exhaust stream must be known. The relative response of the FID to $CH_4$ and $C_2H_6$ shall be determined in accordance with 9.3.3.11.
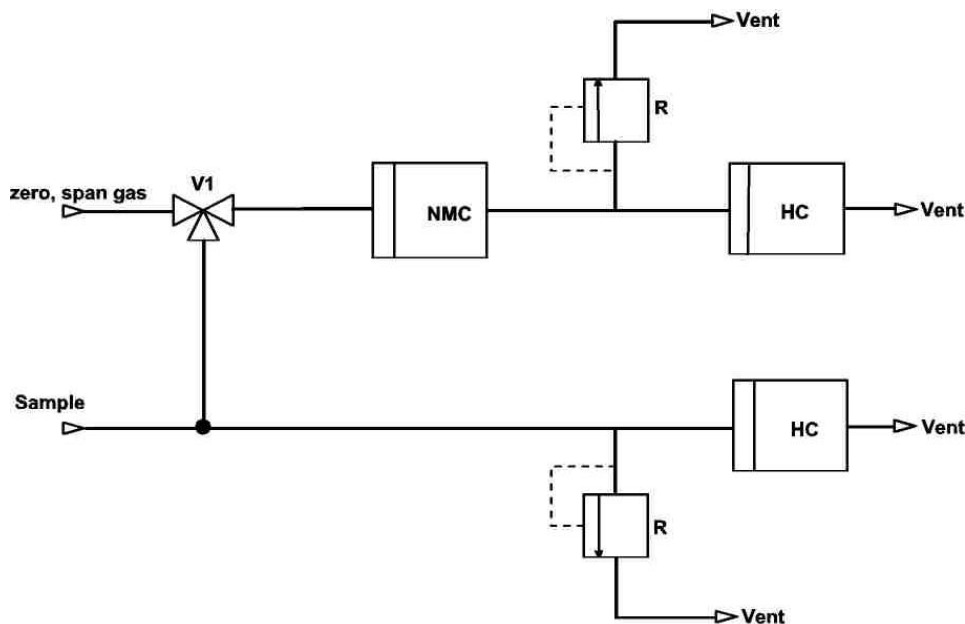


**Figure 8 — Schematic flow diagram of methane analysis with the NMC**

**9.3.4.4.2**         **Components of figure 8**
**NMC**       **Non-methane cutter**

To oxidize all hydrocarbons except methane.

**HC**

Heated flame ionization detector (HFID) or flame ionization detector (FID) to measure the HC and $CH_4$ concentrations. The temperature of the HFID shall be kept at 453 K to 473 K (180°C to 200°C).

**V1**         **Selector valve**

To select zero and span gas

**R**                 **Pressure regulator**

To control the pressure in the sampling line and the flow to the HFID

## 9.4     Particulate Measurement and Sampling System

### 9.4.1     General specifications

To determine the mass of the particulates, a particulate sampling system, particulate sampling filters, a microgram balance, and a temperature and humidity controlled weighing chamber, are required. The particulate sampling system shall be designed to ensure a representative sample of the particulates proportional to the exhaust flow under transient engine operating conditions in accordance with 8.3.3.2.

### 9.4.2     Particulate sampling filters

The diluted exhaust shall be sampled by a filter that meets the requirements of 9.4.2.1 and 9.4.2.2 during the test sequence.

#### 9.4.2.1         Filter specification

Fluorocarbon coated glass fiber filters or fluorocarbon membrane filters are required. All filter types shall have a 0,3 µm DOP (di-octylphthalate) collection efficiency of at least 99 % at a gas face velocity between 35 and 100 cm/s.

#### 9.4.2.2         Filter size

Particulate filters with a diameter of 47 mm or 70 mm are recommended. Larger diameter filters are acceptable (9.4.2.4), but smaller diameter filters are not permitted.

#### 9.4.2.3         Filter face velocity

A gas face velocity through the filter of 0,35 to 1 m/s shall be achieved. The pressure drop increase between the beginning and the end of the test shall be no more than 25 kPa.

#### 9.4.2.4         Filter loading

The required minimum filter loadings for the most common filter sizes are shown in table 8. For larger filter sizes, the minimum filter loading shall be 0,065 mg/1000 mm² filter area.

**Table 8 — Minimum filter loadings**

| Filter Diameter (mm) | Minimum loading (mg) |
|:---:|:---:|
| 47 | 0,11 |
| 70 | 0,25 |
| 90 | 0,41 |
| 110 | 0,62 |

If, based on previous testing, the required minimum filter loading is unlikely to be reached on a test cycle after optimization of flow rates and dilution ratio, the test cycle may be run repeatedly on the same filter without removing it from the filter holder with the agreement of the parties involved. Also, a lower filter loading may be acceptable, with the agreement of the parties involved, if it can be shown to meet the accuracy requirements of 9.4.3.2, e.g. with a balance of 0,1µg resolution.

### 9.4.3     Weighing chamber and analytical balance specifications

#### 9.4.3.1         Weighing chamber conditions

The temperature of the chamber (or room) in which the particulate filters are conditioned and weighed shall be maintained to within 295 K ± 3 K (22°C ± 3°C) during all filter conditioning and weighing. The humidity shall be maintained to a dewpoint of 282,5K ± 3 K (9,5°C ± 3°C) and a relative humidity of 45% ± 8 %.

### 9.4.3.2 Reference filter weighing

The chamber (or room) environment shall be free of any ambient contaminants (such as dust) that would settle on the particulate filters during their stabilization. Disturbances to weighing room specifications as outlined in 9.4.3.1 will be allowed if the duration of the disturbances does not exceed 30 minutes. The weighing room should meet the required specifications prior to personal entrance into the weighing room. At least two unused reference filters shall be weighed within 4 hours of, but preferably at the same time as the sample filter weighings. They shall be the same size and material as the sample filters.

If the average weight of the reference filters changes between sample filter weighings by more than 10 μg, then all sample filters shall be discarded and the emissions test repeated.

If the weighing room stability criteria outlined in 9.4.3.1 is not met, but the reference filter weighings meet the above criteria, the engine manufacturer has the option of accepting the sample filter weights or voiding the tests, fixing the weighing room control system and rerunning the test.

### 9.4.3.3 Analytical balance

The analytical balance used to determine the filter weight shall have a precision (standard deviation) of at least 2 μg and a resolution of at least 1 μg (1 digit = 1 μg) specified by the balance manufacturer.

### 9.4.3.4 Elimination of static electricity effects

If unstable or irreproducible filter weighings are observed due to the effects of static electricity, the filters shall be neutralized prior to weighing, e.g. by a Polonium neutralizer or a device of similar effect.

## 9.4.4 Specifications for flow measurement

Absolute accuracies of flow meter or flow measurement instrumentation shall be as specified in 9.2. For partial flow dilution systems, the accuracy of the sample flow $q_{mp}$ is of special concern, if not measured directly, but determined by differential flow measurement:

$$q_{mp} = q_{mdew} - q_{mdw} \tag{67}$$

In this case an accuracy of $\pm$ 2 % for $q_{mdew}$ and $q_{mdw}$ is not sufficient to guarantee acceptable accuracies of $q_{mp}$. If the gas flow is determined by differential flow measurement, the maximum error of the difference shall be such that the accuracy of $q_{mp}$ is within $\pm$ 5 % when the dilution ratio is less than 15. It can be calculated by taking root-mean-square of the errors of each instrument.

Acceptable accuracies of $q_{mp}$ can be obtained by either of the following methods:

a) The absolute accuracies of $q_{mdew}$ and $q_{mdw}$ are $\pm$ 0,2 % which guarantees an accuracy of $q_{mp}$ of $\leq$ 5 % at a dilution ratio of 15. However, greater errors will occur at higher dilution ratios.

b) Calibration of $q_{mdw}$ relative to $q_{mdew}$ is carried out such that the same accuracies for $q_{mp}$ as in a) are obtained. For the details of such a calibration see clause 9.6.2.

c) The accuracy of $q_{mp}$ is determined indirectly from the accuracy of the dilution ratio as determined by a tracer gas, e.g. $CO_2$. Again, accuracies equivalent to method a) for $q_{mp}$ are required.

d) The absolute accuracy of $q_{mdew}$ and $q_{mdw}$ is within $\pm$ 2 % of full scale, the maximum error of the difference between $q_{mdew}$ and $q_{mdw}$ is within 0,2 %, and the linearity error is within $\pm$ 0,2 % of the highest $q_{mdew}$ observed during the test.

### 9.4.4.1 Correction for sample flow

If measurement of gaseous emissions is done with a total sampling type partial flow dilution system, it is necessary to extract a sample flow $q_{mex}$ from the tunnel, i.e. before the flow measuring device for $q_{mdew}$. $q_{mex}$ shall be determined with the flow measurement device FM shown in figures 6 and 8, and will usually be much smaller than $q_{mdew}$, but not negligible ($q_{mex} > 0,01 \times q_{mdew}$).

In order to guarantee an accuracy of $q_{mp}$ as requested in 9.4.4 and 9.6.2.1, any of the methods outlined in these clauses may be used, but with $q_{mdew}$ replaced by $q_{mdew} + q_{mex}$.

For the calculation of the PM mass emission (see 8.3.3.5), the mass of $q_{mex}$ extracted from the tunnel shall be taken into account by correcting the particulate mass $m_f$, as follows:

$$m_{f,corrected} = m_f \times \frac{q_{mdew}}{\left(q_{mdew} - q_{mex}\right)} \tag{68}$$

### 9.4.5 Additional specifications

All parts of the dilution system and the sampling system from the exhaust pipe up to the filter holder, which are in contact with raw and diluted exhaust gas, shall be designed to minimize deposition or alteration of the particulates. All parts shall be made of electrically conductive materials that do not react with exhaust gas components, and shall be electrically grounded to prevent electrostatic effects.

## 9.5 Dilution and sampling system

### 9.5.1 Introduction

Clause 9.5.2 and figures 9 to 12 contain general descriptions of the recommended dilution and sampling systems. Since various configurations can produce equivalent results, exact conformance with these figures is not required. Additional components such as instruments, valves, solenoids, pumps, and switches may be used to provide additional information and coordinate the functions of the component systems. Other components which are not needed to maintain the accuracy on some systems, may be excluded if their exclusion is based upon good engineering judgment.

### 9.5.2 Description of partial flow system

A dilution system is described based upon the dilution of a part of the exhaust stream. Splitting of the exhaust stream and the following dilution process may be done by different dilution system types. For subsequent collection of the particulates, the entire dilute exhaust gas or only a portion of the dilute exhaust gas is passed to the particulate sampling system. The first method is referred to as total sampling type, the second method as fractional sampling type. The calculation of the dilution ratio depends upon the type of system used.
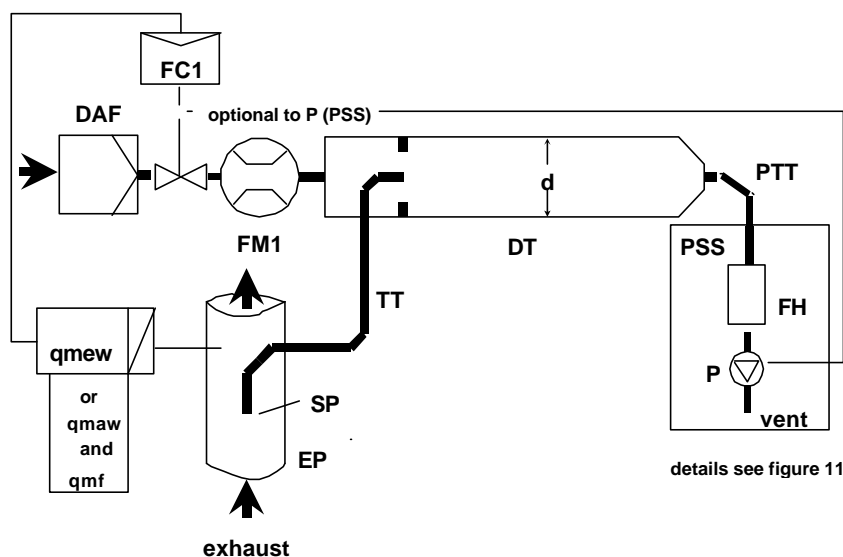


**Figure 9 — Schematic of partial flow dilution system (total sampling type)**

With the total sampling system as shown in figure 9, raw exhaust gas is transferred from the exhaust pipe EP to the dilution tunnel DT through the sampling probe SP and the transfer tube TT. The total flow through the tunnel is adjusted with the flow controller FC2 and the sampling pump P of the particulate sampling system (see figure 12). The dilution air flow is controlled by the flow controller FC1, which may use $q_{mew}$ or $q_{maw}$ and $q_{mf}$ as command signals, for the desired exhaust split. The sample flow into DT is the difference of the total flow and the dilution air flow. The dilution air flow rate is measured with the flow measurement device FM1, the total flow rate with the flow measurement device FM3 of the particulate sampling system (see figure 12). The dilution ratio is calculated from these two flow rates.
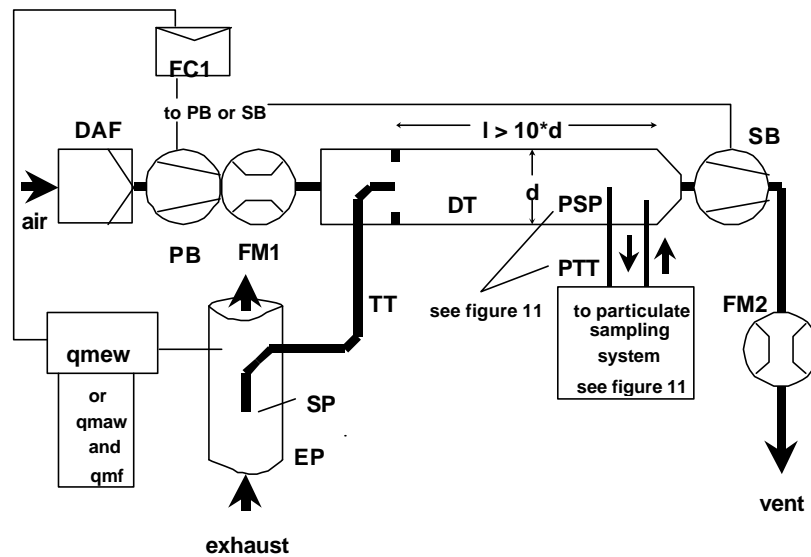
**Figure 10 — Schematic of partial flow dilution system (fractional sampling type)**

With the fractional sampling system as shown in figure 10, raw exhaust gas is transferred from the exhaust pipe EP to the dilution tunnel DT through the sampling probe SP and the transfer tube TT. The total flow through the tunnel is adjusted with the flow controller FC1 connected either to the dilution air flow or to the suction blower for the total tunnel flow. The flow controller FC1 may use $q_{mew}$ or $q_{maw}$ and $q_{mf}$ as command signals for the desired exhaust split. The sample flow into DT is the difference of the total flow and the dilution air flow. The dilution air flow rate is measured with the flow measurement device FM1, the total flow rate with the flow measurement device FM2. The dilution ratio is calculated from these two flow rates. From DT, a particulate sample is taken with the particulate sampling system (see figure 11).

### 9.5.2.1        Components of figures 9 and 10

**EP Exhaust pipe**

The exhaust pipe may be insulated. To reduce the thermal inertia of the exhaust pipe a thickness to diameter ratio of 0,015 or less is recommended. The use of flexible sections shall be limited to a length to diameter ratio of 12 or less. Bends will be minimized to reduce inertial deposition. If the system includes a test bed silencer the silencer may also be insulated. It is recommended to have a straight pipe of 6 pipe diameters upstream and 3 pipe diameters downstream of the tip of the probe.

**SP Sampling probe**

The type of probe shall be either of the following

a)        open tube facing upstream on the exhaust pipe centerline

b)        open tube facing downstream on the exhaust pipe centerline

c)        multiple hole probe as described under SP in clause 9.3.4.3, figure 6

d)        hatted probe facing upstream on the exhaust pipe centerline as shown in figure 11

The minimum inside diameter of the probe tip shall be 4 mm. The minimum diameter ratio between exhaust pipe and probe shall be 4 for probes b) to d). For probe a), the exhaust pipe diameter, the probe diameter and the flow rates shall be set as to allow a maximum sampling error of $0,98 \leq P \leq 1,02$ as determined in accordance with Annex B.

NOTE        When using an open tube facing upstream on the exhaust pipe centerline, special caution should be applied with regard to the impact of large particles not related to combustion products from the cycle under test. Such particles may easily enter the probe which will result in an erroneous PM measurement. A typical example of such particles not related to the actual test are particles from the muffler or particles re-entrained from the exhaust pipe into the exhaust flow. Therefore, an inertial pre-classifier (cyclone or impactor) with at 50% cutpoint between 2.5 and 10 microns is recommended to be installed immediately upstream of the filter holder.
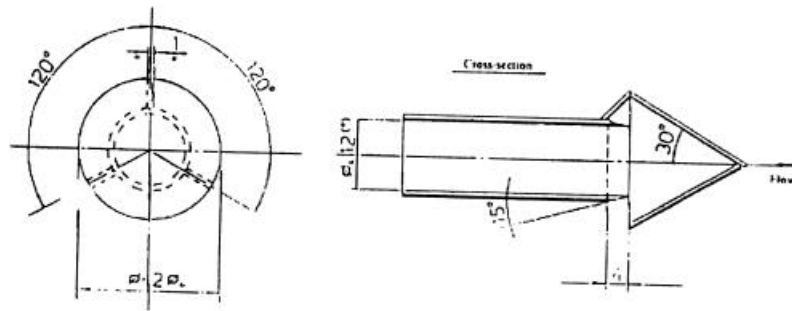
**Figure 11 — Schematic of hatted probe**

**TT Exhaust transfer tube**

The transfer tube shall be:

- as short as possible, but not more than 1 m in length.

- equal to or greater than the probe diameter, but not more than 25 mm in diameter.

- exiting on the centerline of the dilution tunnel and pointing downstream.

The tube shall be insulated with material with a maximum thermal conductivity of 0,05 W/m x K with a radial insulation thickness corresponding to the diameter of the probe, or heated.

**FC1 Flow controller**

A flow controller may be used to control the flow of the pressure blower PB and/or the suction blower SB. It may be connected to the exhaust flow sensor signals specified in 8.3.1. The flow controller may be installed upstream or downstream of the respective blower. When using a pressurized air supply, FC1 directly controls the air flow.

**FM1 Flow measurement device**

Gas meter or other flow instrumentation to measure the dilution air flow. FM1 is optional if the pressure blower PB is calibrated to measure the flow.

**DAF Dilution air filter**

It is recommended that the dilution air be filtered and charcoal scrubbed to eliminate background hydrocarbons. The dilution air shall have a temperature of higher than 288 K (15°C), and may be dehumidified. The dilution air may be sampled according to good engineering practice to determine the background particulate levels, which can then be subtracted from the values measured in the diluted exhaust (see clause 8.3.3.4).

**FM2 — Flow measurement device (fractional sampling type, figure 10, only)**

Gas meter or other flow instrumentation to measure the diluted exhaust gas flow. FM2 is optional if the suction blower SB is calibrated to measure the flow.

**PB — Pressure blower (fractional sampling type, figure 10, only)**

To control the dilution air flow rate. PB may be connected to the flow controllers FC1 or FC2. PB is not required when using a butterfly valve. PB may be used to measure the dilution air flow, if calibrated.

**SB — Suction blower (fractional sampling type, figure 10, only)**

For fractional sampling systems only. SB may be used to measure the diluted exhaust gas flow, if calibrated.

**DT Dilution tunnel**

The dilution tunnel:

- shall be of a sufficient length to cause complete mixing of the exhaust and dilution air under turbulent flow conditions for a fractional sampling system, i.e. complete mixing is not required for a total sampling system.

- shall be constructed of stainless steel

- shall be at least 75 mm in diameter for the fractional sampling type.

- is recommended to be at least 25 mm in diameter for the total sampling type.

- may be heated to no greater than 325 K (52°C) wall temperature.

- may be insulated.

**PSP — Particulate sampling probe (fractional sampling type, figure 10, only)**

The particulate sampling probe is the leading section of the particulate transfer tube PTT and

- shall be installed facing upstream at a point where the dilution air and exhaust gas are well mixed, i.e. on the dilution tunnel DT centerline approximately 10 tunnel diameters downstream of the point where the exhaust enters the dilution tunnel;

- shall be 12 mm in minimum inside diameter;

- may be heated to no greater than 325 K (52 °C) wall temperature by direct heating or by dilution air pre-heating, provided the air temperature does not exceed 325 K (52 °C) prior to the introduction of the exhaust into the dilution tunnel;

- may be insulated.

**PTT  Particulate transfer tube**

The particulate transfer tube shall not exceed 1020 mm in length, and shall be minimized in length whenever possible.

The dimensions are valid for:

- the *fractional sampling* type from the probe tip to the filter holder.

- the *total sampling* type from the end of the dilution tunnel to the filter holder.

The transfer tube:

- may be heated to no greater than 325K (52°C) wall temperature.

- may be insulated.

## 9.5.3    Description of full flow dilution system

A dilution system is described based upon the dilution of the total exhaust using the CVS (constant volume sampling) concept and is shown in figure 12. The total volume of the mixture of exhaust and dilution air shall be measured. Either a PDP or a CFV system may be used.

For subsequent collection of the particulates, a sample of the dilute exhaust gas is passed to the particulate sampling system (see 9.5.4, figure13). If this is done directly, it is referred to as single dilution. If the sample is diluted once more in the secondary dilution tunnel, it is referred to as double dilution. This is useful if the filter face temperature requirement cannot be met with single dilution. Although partly a dilution system, the double dilution system is described as a modification of a particulate sampling system in 9.5.4, figure 13, since it shares most of the parts with a typical particulate sampling system.
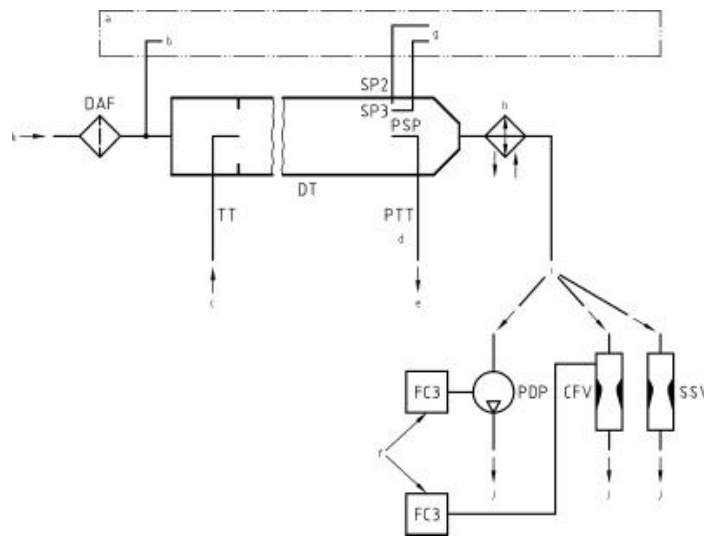
**Figure 12 — Schematic of full flow dilution system (CVS)**

The total amount of raw exhaust gas is mixed in the dilution tunnel DT with the dilution air.

The diluted exhaust gas flow rate is measured either with a positive displacement pump PDP, with a critical flow venturi CFV or with a subsonic venturi SSV. A heat exchanger HE or electronic flow compensation EFC may be used for proportional particulate sampling and for flow determination. Since particulate mass determination is based on the total diluted exhaust gas flow it is not necessary to calculate the dilution ratio.

**9.5.3.1      Components of figure 12**

**EP — exhaust pipe**

The exhaust pipe length from the exit of the engine exhaust manifold, turbocharger outlet or after-treatment device to the dilution tunnel shall be not more than 10 m. If the system exceeds 4 m in length, then all tubing in excess of 4 m shall be insulated, except for an in-line smokemeter, if used. The radial thickness of the insulation shall be at least 25 mm. The thermal conductivity of the insulating material shall have a value no greater than 0,1 W/(m·K) measured at 673 K. To reduce the thermal inertia of the exhaust pipe a thickness-to-diameter ratio of 0,015 or less is recommended. The use of flexible sections shall be limited to a length-to-diameter ratio of 12 or less.

**PDP — positive displacement pump**

The PDP meters total diluted exhaust flow from the number of the pump revolutions and the pump displacement. The exhaust system backpressure shall not be artificially lowered by the PDP or dilution air inlet system. Static exhaust backpressure measured with the PDP system operating shall remain within ± 1,5 kPa of the static pressure measured without connection to the PDP at identical engine speed and load. The gas mixture temperature immediately ahead of the PDP shall be within ± 6 K of the average operating temperature observed during the test, when no flow compensation is used. Flow compensation can only be used if the temperature at the inlet to the PDP does not exceed 323 K (50 °C).

**CFV — critical flow venturi**

CFV measures total diluted exhaust flow by maintaining the flow at chocked conditions (critical flow). Static exhaust backpressure measured with the CFV system operating shall remain within ± 1,5 kPa of the static pressure measured without connection to the CFV at identical engine speed and load. The gas mixture temperature immediately ahead of the CFV shall be within ± 11 K of the average operating temperature observed during the test, when no flow compensation is used.

**SSV — subsonic venturi**

SSV measures total diluted exhaust flow by using the gas flow function of a subsonic venturi in dependence of inlet pressure and temperature and pressure drop between venturi inlet and throat. Static exhaust backpressure measured with the SSV system operating shall remain within ± 1,5 kPa of the static pressure measured without connection to the SSV at identical engine speed and load. The gas mixture temperature immediately ahead of the SSV shall be within ± 11 K of the average operating temperature observed during the test, when no flow compensation is used.

**HE — heat exchanger (optional, if EFC is used)**

The heat exchanger shall be of sufficient capacity to maintain the temperature within the limits required above.

**EFC — electronic flow compensation (optional, if HE is used)**

If the temperature at the inlet to either the PDP or CFV is not kept within the limits stated above, a flow compensation system is required for continuous measurement of the flow rate and control of the proportional sampling in the particulate system. For that purpose, the continuously measured flow rate signals are used accordingly to correct the sample flow rate through the particulate filters of the particulate sampling system (see figure 13).

**DT — dilution tunnel**

The dilution tunnel

— shall be small enough in diameter to cause turbulent flow (Reynolds Number greater than 4000) and of sufficient length to cause complete mixing of the exhaust and dilution air. A mixing orifice may be used;

— shall be at least 75 mm in diameter;

— may be insulated.

The engine exhaust shall be directed downstream at the point where it is introduced into the dilution tunnel, and thoroughly mixed.

When using single dilution, a sample from the dilution tunnel is transferred to the particulate sampling system (see 9.5.4, figure 13). The flow capacity of the PDP or CFV shall be sufficient to maintain the diluted exhaust at a temperature between 315 K (42 °C) and 325 K (52 °C) immediately before the particulate filter.

When using double dilution, a sample from the dilution tunnel is transferred to the secondary dilution tunnel where it is further diluted, and then passed through the sampling filters (9.5.4, figure 22). The flow capacity of the PDP or CFV must be sufficient to maintain the diluted exhaust stream in the DT at a temperature of less than or equal to 464 K (191 °C) at the sampling zone. The secondary dilution system shall provide sufficient secondary dilution air to maintain the doubly diluted exhaust stream at a temperature between 315 K (42 °C) and 325 K (52 °C) immediately before the particulate filter.

**DAF — dilution air filter**

It is recommended that the dilution air be filtered and charcoal scrubbed to eliminate background hydrocarbons. The dilution air shall have a temperature of greater than 288 K (15 °C), and may be dehumidified. At the engine manufacturer's request the dilution air may be sampled according to good engineering practice to determine the background particulate levels, which can then be subtracted from the values measured in the diluted exhaust (see 8.3.3.4).

**PSP — particulate sampling probe**

The probe is the leading section of PTT and

— shall be installed facing upstream at a point where the dilution air and exhaust gases are well mixed, i.e. on the dilution tunnel DT centreline of the dilution systems, approximately 10 tunnel diameters downstream of the point where the exhaust enters the dilution tunnel;

— shall be of 12 mm minimum inside diameter;

— may be heated to no greater than 325 K (52 °C) wall temperature by direct heating or by dilution air pre-heating, provided the air temperature does not exceed 325 K (52 °C) prior to the introduction of the exhaust in the dilution tunnel;

— may be insulated.

## 9.5.4 Description of particulate sampling system

The particulate sampling system is required for collecting the particulates on the particulate filter and is shown in figure 13. In the case of total sampling partial flow dilution, which consists of passing the entire diluted exhaust sample through the filters, the dilution (see 9.5.2, figure 9) and sampling systems usually form an integral unit. In the case of fractional sampling partial flow dilution or full flow dilution, which consists of passing through the filters only a portion of the diluted exhaust, the dilution (see 9.5.2, figure 10, 9.5.3, figure 12) and sampling systems usually form different units.
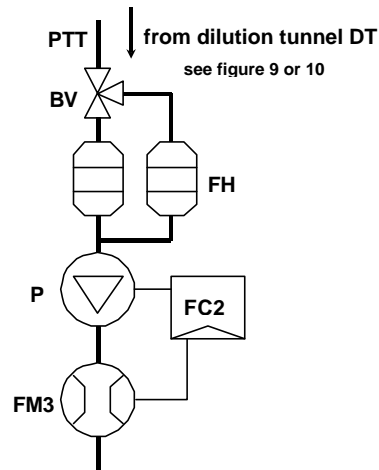


**Figure 13 —  Schematic of particulate sampling system**

### 9.5.4.1 Components of figure 13

**FH Filter holder**

The filter holder:

- may be heated to no greater than 325 K (52°C) wall temperature.

- may be insulated.

An inertial pre-classifier with a 50% cut point between 2,5 μm and 10 μm may be installed immediately upstream of the filter holder. The use of the pre-classifier is strongly recommended, if an open tube sampling probe facing upstream is used.

**P Sampling pump**

**FC2 — Flow controller**

A flow controller shall be used for controlling the particulate sample flow rate.

**FM3 — Flow measurement device**

Gas meter or flow instrumentation to determine the particulate sample flow through the particulate filter. It may be installed upstream or downstream of the sampling pump, P.

**BV — Ball valve (optional)**

The ball valve shall have an inside diameter not less than the inside diameter of the particulate transfer tube PTT, and a switching time of less than 0,5 s.

NOTE      If the ambient temperature in the vicinity of PSP, PTT, SDT and FH is below 293 K (20 °C), precautions should be taken to avoid particle losses on to the cool wall of these parts. Therefore, heating and/or insulating these parts within the limits given in the respective descriptions is recommended. It is also recommended that the filter face temperature during sampling be above 293 K (20 °C).

## 9.6    Calibration

### 9.6.1    Introduction

The calibration of the particulate measurement is limited to the flow meters used to determine sample flow and dilution ratio. Each flow meter shall be calibrated as often as necessary to fulfill the accuracy requirements of this standard. The calibration method that shall be used is described in 9.6.2.

### 9.6.2    Flow measurement

#### 9.6.2.1        Periodical calibration

To fulfill the absolute accuracy of the flow measurements as specified in 9.2, the flow meter or the flow measurement instrumentation shall be calibrated with an accurate flow meter traceable to international and/or national standards.

If the sample gas flow is determined by differential flow measurement the flow meter or the flow measurement instrumentation shall be calibrated in one of the following procedures, such that the probe flow $q_{mp}$ into the tunnel shall fulfill the accuracy requirements of clause 9.4.4:

a) The flow meter for $q_{mdw}$ shall be connected in series to the flow meter for $q_{mdew}$, the difference between the two flow meters shall be calibrated for at least  5 set points with flow values equally spaced between the lowest $q_{mdw}$ value used during the test and the value of $q_{mdew}$ used during the test. The dilution tunnel may be bypassed.

b) A calibrated mass flow device shall be connected in series to the flowmeter for $q_{mdew}$ and the accuracy shall be checked for the value used for the test. Then the calibrated mass flow device shall be connected in series to the flow meter for $q_{mdw}$, and the accuracy shall be checked for at least 5 settings corresponding to dilution ratio between 3 and 50, relative to $q_{mdew}$ used during the test.

c) The transfer tube TT shall be disconnected from the exhaust, and a calibrated flow measuring device with a suitable range to measure $q_{mp}$ shall be connected to the transfer tube. Then $q_{mdew}$ shall be set to the value used during the test, and $q_{mdw}$ shall be sequentially set to at least 5 values corresponding to dilution ratios q between 3 and 50. Alternatively, a special calibration flow path, may be provided, in which the tunnel is bypassed, but the total and dilution air flow through the corresponding meters as in the actual test.

d) A tracer gas, shall be fed into the exhaust transfer tube TT. This tracer gas may be a component of the exhaust gas, like $CO_2$ or NOx. After dilution in the tunnel the tracer gas component shall be measured. This shall be carried out for 5 dilution ratios between 3 and 50. The accuracy of the sample flow shall be determined from the dilution ration $r_d$:

$$q_{mp} = q_{mdew} / r_d \tag{69}$$

The accuracies of the gas analyzers shall be taken into account to guarantee the accuracy of $q_{mp}$.

#### 9.6.2.2        Carbon flow check

A carbon flow check using actual exhaust is strongly recommended for detecting measurement and control problems and verifying the proper operation of the partial flow system. The carbon flow check should be run at least each time a new engine is installed, or something significant is changed in the test cell configuration.

The engine shall be operated at peak torque load and speed or any other steady state mode that produces 5% or more of $CO_2$. The partial flow sampling system shall be operated with a dilution factor of about 15 to 1.

If a carbon flow check is conducted, the procedure given in Annex 10.5 shall be applied. The carbon flow rates shall be calculated according to equations 80 to 82. All carbon flow rates should agree to within 3 %.

#### 9.6.2.3        Pre-test check

A pre-test check shall be performed within 2 hours before the test run in the following way:

The accuracy of the flow meters shall be checked by the same method as used for calibration (see clause 9.6.2.1) for at least two points, including flow values of $q_{mdw}$ that correspond to dilution ratios between 5 and 15 for the $q_{mdew}$ value used during the test.

If it can be demonstrated by records of the calibration procedure under clause 9.6.2.1 that the flow meter calibration is stable over a longer period of time, the pre-test check may be omitted.

### 9.6.3 Determination of the transformation time

The system settings for the transformation time evaluation shall be exactly the same as during measurement of the test run. The transformation time shall be determined by the following method:

An independent reference flowmeter with a measurement range appropriate for the probe flow shall be put in series with and closely coupled to the probe. This flowmeter shall have a transformation time of less than 100 ms for the flow step size used in the response time measurement, with flow restriction sufficiently low as to not affect the dynamic performance of the partial flow dilution system, and consistent with good engineering practice.

A step change shall be introduced to the exhaust flow (or air flow if exhaust flow is calculated) input of the partial flow dilution system, from a low flow to at least 90% of full scale. The trigger for the step change should be the same one used to start the look-ahead control in actual testing. The exhaust flow step stimulus and the flowmeter response shall be recorded at a sample rate of at least 10 Hz.

From this data, the transformation time shall be determined for the partial flow dilution system, which is the time from the initiation of the step stimulus to the 50% point of the flowmeter response. In a similar manner, the transformation times of the $q_{mp}$ signal of the partial flow dilution system and of the $q_{mew,i}$ signal of the exhaust flow meter shall be determined.  These signals are used in the regression checks performed after each test (see clause 8.3.3.3)

The calculation shall be repeated for at least 5 rise and fall stimuli, and the results shall be averaged. The internal transformation time (<100 msec) of the reference flowmeter shall be subtracted from this value. This is the "look-ahead" value of the partial flow dilution system, which shall be applied in accordance with clause 8.3.3.3.

### 9.6.4 Calibration of the CVS system

#### 9.6.4.1 General

The CVS system shall be calibrated by using an accurate flowmeter and a restricting device.  The flow through the system shall be measured at different restriction settings, and the control parameters of the system shall be measured and related to the flow.

Various type of flowmeters may be used, e.g. calibrated venturi, calibrated laminar flowmeter, calibrated turbinemeter.

#### 9.6.4.2 Calibration of the Positive Displacement Pump (PDP)

All the parameters related to the pump shall be simultaneously measured along with the parameters related to a calibration venturi which is connected in series with the pump. The calculated flow rate (in $m^3$/min at pump inlet, absolute pressure and temperature) shall be plotted versus a correlation function which is the value of a specific combination of pump parameters. The linear equation which relates the pump flow and the correlation function shall be determined. If a CVS has a multiple speed drive, the calibration shall be performed for each range used.

Temperature stability shall be maintained during calibration.

Leaks in all the connections and ducting between the calibration venturi and the CVS pump shall be maintained lower than 0.3% of the lowest flow point (highest restriction and lowest PDP speed point).

#### 9.6.4.2.1 Data analysis

The air flowrate ($Q_s$) at each restriction setting (minimum 6 settings) shall be calculated in standard m3/min from the flowmeter data using the manufacturer's prescribed method. The air flow rate shall then be converted to pump flow ($V_0$) in $m^3$/rev at absolute pump inlet temperature and pressure as follows:

$$V_0 = \frac{Q_s}{n} * \frac{T}{273} * \frac{101.3}{p_A}$$

(70

where,

$Q_s$ = air flow rate at standard conditions (101,3 kPa, 273 K), $m^3$/s

$T$ = temperature at pump inlet, K

$p_A$ = absolute pressure at pump inlet ($p_B$- $p_1$), kPa

$n$ = pump speed, rev/s

To account for the interaction of pressure variations at the pump and the pump slip rate, the correlation function ($X_0$) between pump speed, pressure differential from pump inlet to pump outlet and absolute pump

outlet pressure shall be calculated as follows:

$$X_0 = \frac{1}{n} * \sqrt{\frac{\Delta p_p}{p_A}}$$

(71

where

$\Delta p_p$ = pressure differential from pump inlet to pump outlet, kPa

$p_A$ = absolute outlet pressure at pump outlet, kPa

A linear least-square fit shall be performed to generate the calibration equation as follows:

$$V_0 = D_0 - m * (X_0)$$

(72

$D_0$ and m are the intercept and slope constants, respectively, describing the regression lines.

For a CVS system with multiple speeds, the calibration curves generated for the different pump flow ranges shall be approximately parallel, and the intercept values ($D_0$) shall increase as the pump flow range decreases.

The calculated values from the equation shall be within ± 0,5 % of the measured value of $V_0$. Values of m will vary from one pump to another. Particulate influx over time will cause the pump slip to decrease, as reflected by lower values for m. Therefore, calibration shall be performed at pump start-up, after major maintenance, and if the total system verification indicates a change of the slip rate.

### 9.6.4.3 Calibration of the Critical Flow Venturi (CFV)

Calibration of the CFV is based upon the flow equation for a critical venturi. Gas flow is a function of inlet pressure and temperature, as shown below

$$Q_s = \frac{K_v * p_A}{\sqrt{T}}$$

(73)

where

$K_v$ = calibration coefficient

$p_A$ = absolute pressure at venturi inlet, kPa

$T$ = temperature at venturi inlet, K

### 9.6.4.3.1 Data analysis

The air flowrate ($Q_s$) at each restriction setting (minimum 8 settings) shall be calculated in standard $m^3$/min from the flowmeter data using the manufacturer's prescribed method. The calibration coefficient shall be calculated from the calibration data for each setting as follows:

$$K_v = \frac{Q_S * \sqrt{T}}{p_A}$$

(74

where,

$Q_s$ = air flow rate at standard conditions (101,3 kPa, 273 K), $m^3$/s

$T$ = temperature at the venturi inlet, K

$p_A$ = absolute pressure at venturi inlet, kPa

To determine the range of critical flow, $K_v$ shall be plotted as a function of venturi inlet pressure. For critical (choked) flow, $K_v$ will have a relatively constant value. As pressure decreases (vacuum increases), the venturi becomes unchoked and $K_v$ decreases, which indicates that the CFV is operated outside the permissible range.

For a minimum of eight points in the region of critical flow, the average $K_V$ and the standard deviation shall be calculated. The standard deviation shall not exceed ± 0,3 % of the average $K_V$

### 9.6.4.4 Calibration of the Subsonic Venturi (SSV)

Calibration of the SSV is based upon the flow equation for a subsonic venturi. Gas flow is a function of inlet pressure and temperature, pressure drop between the SSV inlet and throat, as shown below

$$Q_{SSV} = A_0 d^2 C_d P_A \sqrt{\left[\frac{1}{T}\left(r^{1.4286} - r^{1.7143}\right)\left(\frac{1}{1 - \boldsymbol{b}^4 r^{1.4286}}\right)\right]}$$

(75

where

$A_0$ = collection of constants and units conversions

= 0,006111 in SI units of $\left(\dfrac{m^3}{\min}\right)\left(\dfrac{K^{\frac{1}{2}}}{kPa}\right)\left(\dfrac{1}{mm^2}\right)$

$d$ = diameter of the SSV throat, m

$C_d$ = discharge coefficient of the SSV

$P_A$ = absolute pressure at venturi inlet, kPa

$T$ = temperature at the venturi inlet, K

$r$ = ratio of the SSV throat to inlet absolute, static pressure = $1 - \dfrac{\Delta P}{P_A}$

$\beta$ = ratio of the SSV throat diameter, d, to the inlet pipe inner diameter = $\dfrac{d}{D}$

### 9.6.4.4.1 Data analysis

The air flowrate ($Q_{SSV}$) at each restriction setting (minimum 16 settings) shall be calculated in standard $m^3$/min from the flowmeter data using the manufacturer's prescribed method. The discharge coefficient shall be calculated from the calibration data for each setting as follows:

$$C_d = \frac{Q_{SSV}}{d^2 P_A \sqrt{\left[\frac{1}{T}\left(r^{1.4286} - r^{1.7143}\right)\left(\frac{1}{1 - \boldsymbol{b}^4 r^{1.4286}}\right)\right]}}$$

(76

where

$Q_{SSV}$ = air flow rate at standard conditions (101,3 kPa, 273 K), $m^3$/s

$T$ = temperature at the venturi inlet, K

$d$ = diameter of the SSV throat, m

$r$ = ratio of the SSV throat to inlet absolute, static pressure = $1 - \dfrac{\Delta P}{P_A}$

$\beta$ = ratio of the SSV throat diameter, d, to the inlet pipe inner diameter = $\dfrac{d}{D}$

To determine the range of subsonic flow, $C_d$ shall be plotted as a function of Reynolds number, at the SSV throat. The Re at the SSV throat is calculated with the following formula:

$$\text{Re} = A_1 \frac{Q_{SSV}}{d\boldsymbol{m}}$$

(77

where

<u>A$_1$</u> = a collection of constants and units conversions

$$= 25{,}55152 \left(\frac{1}{m^3}\right)\left(\frac{\min}{s}\right)\left(\frac{mm}{m}\right)$$

Q$_{SSV}$ = air flow rate at standard conditions (101,3 kPa, 273 K), m$^3$/s

d = diameter of the SSV throat, m

μ = absolute or dynamic viscosity of the gas, calculated with the following formula:

$$\boldsymbol{m} = \frac{bT^{3/2}}{S+T} = \frac{bT^{1/2}}{1+\dfrac{S}{T}} \ \text{kg/m-s}$$

(78

b = empirical constant $\quad = {.}1{,}458 \times 10^6 \ \dfrac{kg}{msK^{\frac{1}{2}}}$

S = empirical constant $\quad = 110{,}4\,K$

Because Q$_{SSV}$ is an input to the Re formula, the calculations must be started with an initial guess for Q$_{SSV}$ or C$_d$ of the calibration venturi, and repeated until Q$_{SSV}$ converges. The convergence method must be accurate to 0.1% of point or better.

For a minimum of sixteen points in the region of subsonic flow, the calculated values of C$_d$ from the resulting calibration curve fit equation must be within ± 0.5% of the measured C$_d$ for each calibration point.

### 9.6.4.5 Total system verification

The total accuracy of the CVS sampling system and analytical system shall be determined by introducing a known mass of a pollutant gas into the system while it is being operated in the normal manner. The pollutant is analysed, and the mass calculated according to 8.4.2.4 except in the case of propane where a factor of 0,000472 is used in place of 0,000479 for HC. Either of the following two techniques shall be used.

### 9.6.4.5.1 Metering with a critical flow orifice

A known quantity of pure gas (carbon monoxide or propane) shall be fed into the CVS system through a calibrated critical orifice. If the inlet pressure is high enough, the flow rate, which is adjusted by means of the critical flow orifice, is independent of the orifice outlet pressure (critical flow). The CVS system shall be operated as in a normal exhaust emission test for about 5 to 10 minutes. A gas sample shall be analysed with the usual equipment (sampling bag or integrating method), and the mass of the gas calculated. The mass so determined shall be within ± 3% of the known mass of the gas injected.

### 9.6.4.5.2 Metering by means of a gravimetric technique

The weight of a small cylinder filled with carbon monoxide or propane shall be determined with a precision of ± 0,01 gram. For about 5 to 10 minutes, the CVS system shall be operated as in a normal exhaust emission test, while carbon monoxide or propane is injected into the system. The quantity of pure gas discharged shall be determined by means of differential weighing. A gas sample shall be analysed with the usual equipment (sampling bag or integrating method), and the mass of the gas calculated. The mass so determined shall be within ± 3% of the known mass of the gas injected.

## 9.6.5 Calibration intervals

The instruments shall be calibrated as required by internal audit procedures, by the instrument manufacturer or in accordance with ISO 9000 requirements.

# 10 Annexes

## 10.1 [Essential Characteristics of the Engine and Information Concerning the Conduct of Tests]

## 10.2 WHTC Engine Dynamometer Schedule

| Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque |
|---|---|---|---|---|---|---|---|---|
| s | % | % | s | % | % | s | % | % |
| 1 | 0,0 | 0,0 | 52 | 26,3 | 25,5 | 103 | 36,2 | 23,5 |
| 2 | 0,0 | 0,0 | 53 | 35,0 | 32,2 | 104 | 36,8 | 22,7 |
| 3 | 0,0 | 0,0 | 54 | 41,7 | 14,3 | 105 | 37,2 | 20,9 |
| 4 | 0,0 | 0,0 | 55 | 42,2 | 0,0 | 106 | 37,0 | 19,2 |
| 5 | 0,0 | 0,0 | 56 | 42,8 | 11,6 | 107 | 36,3 | 18,4 |
| 6 | 0,0 | 0,0 | 57 | 51,0 | 20,9 | 108 | 35,4 | 17,6 |
| 7 | 1,5 | 8,9 | 58 | 60,0 | 9,6 | 109 | 35,2 | 14,9 |
| 8 | 15,8 | 30,9 | 59 | 49,4 | 0,0 | 110 | 35,4 | 9,9 |
| 9 | 27,4 | 1,3 | 60 | 38,9 | 16,6 | 111 | 35,5 | 4,3 |
| 10 | 32,6 | 0,7 | 61 | 43,4 | 30,8 | 112 | 35,2 | 6,6 |
| 11 | 34,8 | 1,2 | 62 | 49,4 | 14,2 | 113 | 34,9 | 10,0 |
| 12 | 36,2 | 7,4 | 63 | 40,5 | 0,0 | 114 | 34,7 | 25,1 |
| 13 | 37,1 | 6,2 | 64 | 31,5 | 43,5 | 115 | 34,4 | 29,3 |
| 14 | 37,9 | 10,2 | 65 | 36,6 | 78,2 | 116 | 34,5 | 20,7 |
| 15 | 39,6 | 12,3 | 66 | 40,8 | 67,6 | 117 | 35,2 | 16,6 |
| 16 | 42,3 | 12,5 | 67 | 44,7 | 59,1 | 118 | 35,8 | 16,2 |
| 17 | 45,3 | 12,6 | 68 | 48,3 | 52,0 | 119 | 35,6 | 20,3 |
| 18 | 48,6 | 6,0 | 69 | 51,9 | 63,8 | 120 | 35,3 | 22,5 |
| 19 | 40,8 | 0,0 | 70 | 54,7 | 27,9 | 121 | 35,3 | 23,4 |
| 20 | 33,0 | 16,3 | 71 | 55,3 | 18,3 | 122 | 34,7 | 11,9 |
| 21 | 42,5 | 27,4 | 72 | 55,1 | 16,3 | 123 | 45,5 | 0,0 |
| 22 | 49,3 | 26,7 | 73 | 54,8 | 11,1 | 124 | 56,3 | m |
| 23 | 54,0 | 18,0 | 74 | 54,7 | 11,5 | 125 | 46,2 | m |
| 24 | 57,1 | 12,9 | 75 | 54,8 | 17,5 | 126 | 50,1 | 0,0 |
| 25 | 58,9 | 8,6 | 76 | 55,6 | 18,0 | 127 | 54,0 | m |
| 26 | 59,3 | 6,0 | 77 | 57,0 | 14,1 | 128 | 40,5 | m |
| 27 | 59,0 | 4,9 | 78 | 58,1 | 7,0 | 129 | 27,0 | m |
| 28 | 57,9 | m | 79 | 43,3 | 0,0 | 130 | 13,5 | m |
| 29 | 55,7 | m | 80 | 28,5 | 25,0 | 131 | 0,0 | 0,0 |
| 30 | 52,1 | m | 81 | 30,4 | 47,8 | 132 | 0,0 | 0,0 |
| 31 | 46,4 | m | 82 | 32,1 | 39,2 | 133 | 0,0 | 0,0 |
| 32 | 38,6 | m | 83 | 32,7 | 39,3 | 134 | 0,0 | 0,0 |
| 33 | 29,0 | m | 84 | 32,4 | 17,3 | 135 | 0,0 | 0,0 |
| 34 | 20,8 | m | 85 | 31,6 | 11,4 | 136 | 0,0 | 0,0 |
| 35 | 16,9 | m | 86 | 31,1 | 10,2 | 137 | 0,0 | 0,0 |
| 36 | 16,9 | 42,5 | 87 | 31,1 | 19,5 | 138 | 0,0 | 0,0 |
| 37 | 18,8 | 38,4 | 88 | 31,4 | 22,5 | 139 | 0,0 | 0,0 |
| 38 | 20,7 | 32,9 | 89 | 31,6 | 22,9 | 140 | 0,0 | 0,0 |
| 39 | 21,0 | 0,0 | 90 | 31,6 | 24,3 | 141 | 0,0 | 0,0 |
| 40 | 19,1 | 0,0 | 91 | 31,9 | 26,9 | 142 | 0,0 | 4,9 |
| 41 | 13,7 | 0,0 | 92 | 32,4 | 30,6 | 143 | 0,0 | 7,3 |
| 42 | 2,2 | 0,0 | 93 | 32,8 | 32,7 | 144 | 4,4 | 28,7 |
| 43 | 0,0 | 0,0 | 94 | 33,7 | 32,5 | 145 | 11,1 | 26,4 |
| 44 | 0,0 | 0,0 | 95 | 34,4 | 29,5 | 146 | 15,0 | 9,4 |
| 45 | 0,0 | 0,0 | 96 | 34,3 | 26,5 | 147 | 15,9 | 0,0 |
| 46 | 0,0 | 0,0 | 97 | 34,4 | 24,7 | 148 | 15,3 | 0,0 |
| 47 | 0,0 | 0,0 | 98 | 35,0 | 24,9 | 149 | 14,2 | 0,0 |
| 48 | 0,0 | 0,0 | 99 | 35,6 | 25,2 | 150 | 13,2 | 0,0 |
| 49 | 0,0 | 0,0 | 100 | 36,1 | 24,8 | 151 | 11,6 | 0,0 |
| 50 | 0,0 | 13,1 | 101 | 36,3 | 24,0 | 152 | 8,4 | 0,0 |
| 51 | 13,1 | 30,1 | 102 | 36,2 | 23,6 | 153 | 5,4 | 0,0 |

| Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque |
|------|------|------|------|------|------|------|------|------|
| s | % | % | s | % | % | s | % | % |
| 154 | 4,3 | 5,6 | 205 | 0,0 | 0,0 | 256 | 33,0 | 53,5 |
| 155 | 5,8 | 24,4 | 206 | 0,0 | 0,0 | 257 | 43,7 | 22,1 |
| 156 | 9,7 | 20,7 | 207 | 0,0 | 0,0 | 258 | 39,8 | 0,0 |
| 157 | 13,6 | 21,1 | 208 | 0,0 | 0,0 | 259 | 36,0 | 45,7 |
| 158 | 15,6 | 21,5 | 209 | 0,0 | 0,0 | 260 | 47,6 | 75,9 |
| 159 | 16,5 | 21,9 | 210 | 0,0 | 0,0 | 261 | 61,2 | 70,4 |
| 160 | 18,0 | 22,3 | 211 | 0,0 | 0,0 | 262 | 72,3 | 70,4 |
| 161 | 21,1 | 46,9 | 212 | 0,0 | 0,0 | 263 | 76,0 | m |
| 162 | 25,2 | 33,6 | 213 | 0,0 | 0,0 | 264 | 74,3 | m |
| 163 | 28,1 | 16,6 | 214 | 0,0 | 0,0 | 265 | 68,5 | m |
| 164 | 28,8 | 7,0 | 215 | 0,0 | 0,0 | 266 | 61,0 | m |
| 165 | 27,5 | 5,0 | 216 | 0,0 | 0,0 | 267 | 56,0 | m |
| 166 | 23,1 | 3,0 | 217 | 0,0 | 0,0 | 268 | 54,0 | m |
| 167 | 16,9 | 1,9 | 218 | 0,0 | 0,0 | 269 | 53,0 | m |
| 168 | 12,2 | 2,6 | 219 | 0,0 | 0,0 | 270 | 50,8 | m |
| 169 | 9,9 | 3,2 | 220 | 0,0 | 0,0 | 271 | 46,8 | m |
| 170 | 9,1 | 4,0 | 221 | 0,0 | 0,0 | 272 | 41,7 | m |
| 171 | 8,8 | 3,8 | 222 | 0,0 | 0,0 | 273 | 35,9 | m |
| 172 | 8,5 | 12,2 | 223 | 0,0 | 0,0 | 274 | 29,2 | m |
| 173 | 8,2 | 29,4 | 224 | 0,0 | 0,0 | 275 | 20,7 | m |
| 174 | 9,6 | 20,1 | 225 | 0,0 | 0,0 | 276 | 10,1 | m |
| 175 | 14,7 | 16,3 | 226 | 0,0 | 0,0 | 277 | 0,0 | m |
| 176 | 24,5 | 8,7 | 227 | 0,0 | 0,0 | 278 | 0,0 | 0,0 |
| 177 | 39,4 | 3,3 | 228 | 0,0 | 0,0 | 279 | 0,0 | 0,0 |
| 178 | 39,0 | 2,9 | 229 | 0,0 | 0,0 | 280 | 0,0 | 0,0 |
| 179 | 38,5 | 5,9 | 230 | 0,0 | 0,0 | 281 | 0,0 | 0,0 |
| 180 | 42,4 | 8,0 | 231 | 0,0 | 0,0 | 282 | 0,0 | 0,0 |
| 181 | 38,2 | 6,0 | 232 | 0,0 | 0,0 | 283 | 0,0 | 0,0 |
| 182 | 41,4 | 3,8 | 233 | 0,0 | 0,0 | 284 | 0,0 | 0,0 |
| 183 | 44,6 | 5,4 | 234 | 0,0 | 0,0 | 285 | 0,0 | 0,0 |
| 184 | 38,8 | 8,2 | 235 | 0,0 | 0,0 | 286 | 0,0 | 0,0 |
| 185 | 37,5 | 8,9 | 236 | 0,0 | 0,0 | 287 | 0,0 | 0,0 |
| 186 | 35,4 | 7,3 | 237 | 0,0 | 0,0 | 288 | 0,0 | 0,0 |
| 187 | 28,4 | 7,0 | 238 | 0,0 | 0,0 | 289 | 0,0 | 0,0 |
| 188 | 14,8 | 7,0 | 239 | 0,0 | 0,0 | 290 | 0,0 | 0,0 |
| 189 | 0,0 | 5,9 | 240 | 0,0 | 0,0 | 291 | 0,0 | 0,0 |
| 190 | 0,0 | 0,0 | 241 | 0,0 | 0,0 | 292 | 0,0 | 0,0 |
| 191 | 0,0 | 0,0 | 242 | 0,0 | 0,0 | 293 | 0,0 | 0,0 |
| 192 | 0,0 | 0,0 | 243 | 0,0 | 0,0 | 294 | 0,0 | 0,0 |
| 193 | 0,0 | 0,0 | 244 | 0,0 | 0,0 | 295 | 0,0 | 0,0 |
| 194 | 0,0 | 0,0 | 245 | 0,0 | 0,0 | 296 | 0,0 | 0,0 |
| 195 | 0,0 | 0,0 | 246 | 0,0 | 0,0 | 297 | 0,0 | 0,0 |
| 196 | 0,0 | 0,0 | 247 | 0,0 | 0,0 | 298 | 0,0 | 0,0 |
| 197 | 0,0 | 0,0 | 248 | 0,0 | 0,0 | 299 | 0,0 | 0,0 |
| 198 | 0,0 | 0,0 | 249 | 0,0 | 0,0 | 300 | 0,0 | 0,0 |
| 199 | 0,0 | 0,0 | 250 | 0,0 | 0,0 | 301 | 0,0 | 0,0 |
| 200 | 0,0 | 0,0 | 251 | 0,0 | 0,0 | 302 | 0,0 | 0,0 |
| 201 | 0,0 | 0,0 | 252 | 0,0 | 0,0 | 303 | 0,0 | 0,0 |
| 202 | 0,0 | 0,0 | 253 | 0,0 | 31,6 | 304 | 0,0 | 0,0 |
| 203 | 0,0 | 0,0 | 254 | 9,4 | 13,6 | 305 | 0,0 | 0,0 |
| 204 | 0,0 | 0,0 | 255 | 22,2 | 16,9 | 306 | 0,0 | 0,0 |

| Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque |
|------|-------------|--------------|------|-------------|--------------|------|-------------|--------------|
| s | % | % | s | % | % | s | % | % |
| 307 | 0,0 | 0,0 | 358 | 36,5 | 50,1 | 409 | 55,5 | 20,3 |
| 308 | 0,0 | 0,0 | 359 | 47,7 | 21,0 | 410 | 55,8 | 5,2 |
| 309 | 0,0 | 0,0 | 360 | 38,8 | 0,0 | 411 | 55,4 | m |
| 310 | 0,0 | 0,0 | 361 | 30,0 | 37,0 | 412 | 54,4 | m |
| 311 | 0,0 | 0,0 | 362 | 37,0 | 63,6 | 413 | 53,1 | m |
| 312 | 0,0 | 0,0 | 363 | 45,5 | 90,8 | 414 | 51,8 | m |
| 313 | 0,0 | 0,0 | 364 | 54,5 | 40,9 | 415 | 50,3 | m |
| 314 | 0,0 | 0,0 | 365 | 45,9 | 0,0 | 416 | 48,4 | m |
| 315 | 0,0 | 0,0 | 366 | 37,2 | 47,5 | 417 | 45,9 | m |
| 316 | 0,0 | 0,0 | 367 | 44,5 | 84,4 | 418 | 43,1 | m |
| 317 | 0,0 | 0,0 | 368 | 51,7 | 32,4 | 419 | 40,1 | m |
| 318 | 0,0 | 0,0 | 369 | 58,1 | 15,2 | 420 | 37,4 | m |
| 319 | 0,0 | 0,0 | 370 | 45,9 | 0,0 | 421 | 35,1 | m |
| 320 | 0,0 | 0,0 | 371 | 33,6 | 35,8 | 422 | 32,8 | m |
| 321 | 0,0 | 0,0 | 372 | 36,9 | 67,0 | 423 | 45,3 | 0,0 |
| 322 | 0,0 | 0,0 | 373 | 40,2 | 84,7 | 424 | 57,8 | m |
| 323 | 0,0 | 0,0 | 374 | 43,4 | 84,3 | 425 | 50,6 | m |
| 324 | 4,5 | 41,0 | 375 | 45,7 | 84,3 | 426 | 41,6 | m |
| 325 | 17,2 | 38,9 | 376 | 46,5 | m | 427 | 47,9 | 0,0 |
| 326 | 30,1 | 36,8 | 377 | 46,1 | m | 428 | 54,2 | m |
| 327 | 41,0 | 34,7 | 378 | 43,9 | m | 429 | 48,1 | m |
| 328 | 50,0 | 32,6 | 379 | 39,3 | m | 430 | 47,0 | 31,3 |
| 329 | 51,4 | 0,1 | 380 | 47,0 | m | 431 | 49,0 | 38,3 |
| 330 | 47,8 | m | 381 | 54,6 | m | 432 | 52,0 | 40,1 |
| 331 | 40,2 | m | 382 | 62,0 | m | 433 | 53,3 | 14,5 |
| 332 | 32,0 | m | 383 | 52,0 | m | 434 | 52,6 | 0,8 |
| 333 | 24,4 | m | 384 | 43,0 | m | 435 | 49,8 | m |
| 334 | 16,8 | m | 385 | 33,9 | m | 436 | 51,0 | 18,6 |
| 335 | 8,1 | m | 386 | 28,4 | m | 437 | 56,9 | 38,9 |
| 336 | 0,0 | m | 387 | 25,5 | m | 438 | 67,2 | 45,0 |
| 337 | 0,0 | 0,0 | 388 | 24,6 | 11,0 | 439 | 78,6 | 21,5 |
| 338 | 0,0 | 0,0 | 389 | 25,2 | 14,7 | 440 | 65,5 | 0,0 |
| 339 | 0,0 | 0,0 | 390 | 28,6 | 28,4 | 441 | 52,4 | 31,3 |
| 340 | 0,0 | 0,0 | 391 | 35,5 | 65,0 | 442 | 56,4 | 60,1 |
| 341 | 0,0 | 0,0 | 392 | 43,8 | 75,3 | 443 | 59,7 | 29,2 |
| 342 | 0,0 | 0,0 | 393 | 51,2 | 34,2 | 444 | 45,1 | 0,0 |
| 343 | 0,0 | 0,0 | 394 | 40,7 | 0,0 | 445 | 30,6 | 4,2 |
| 344 | 0,0 | 0,0 | 395 | 30,3 | 45,4 | 446 | 30,9 | 8,4 |
| 345 | 0,0 | 0,0 | 396 | 34,2 | 83,1 | 447 | 30,5 | 4,3 |
| 346 | 0,0 | 0,0 | 397 | 37,6 | 85,3 | 448 | 44,6 | 0,0 |
| 347 | 0,0 | 0,0 | 398 | 40,8 | 87,5 | 449 | 58,8 | m |
| 348 | 0,0 | 0,0 | 399 | 44,8 | 89,7 | 450 | 55,1 | m |
| 349 | 0,0 | 0,0 | 400 | 50,6 | 91,9 | 451 | 50,6 | m |
| 350 | 0,0 | 0,0 | 401 | 57,6 | 94,1 | 452 | 45,3 | m |
| 351 | 0,0 | 0,0 | 402 | 64,6 | 44,6 | 453 | 39,3 | m |
| 352 | 0,0 | 0,0 | 403 | 51,6 | 0,0 | 454 | 49,1 | 0,0 |
| 353 | 0,0 | 0,0 | 404 | 38,7 | 37,4 | 455 | 58,8 | m |
| 354 | 0,0 | 0,5 | 405 | 42,4 | 70,3 | 456 | 50,7 | m |
| 355 | 0,0 | 4,9 | 406 | 46,5 | 89,1 | 457 | 42,4 | m |
| 356 | 9,2 | 61,3 | 407 | 50,6 | 93,9 | 458 | 44,1 | 0,0 |
| 357 | 22,4 | 40,4 | 408 | 53,8 | 33,0 | 459 | 45,7 | m |

| Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque |
|------|-------------|--------------|------|-------------|--------------|------|-------------|--------------|
| s | % | % | s | % | % | s | % | % |
| 460 | 32,5 | m | 511 | 51,4 | 42,4 | 562 | 53,4 | 20,7 |
| 461 | 20,7 | m | 512 | 52,5 | 31,9 | 563 | 54,2 | 13,1 |
| 462 | 10,0 | m | 513 | 53,7 | 21,6 | 564 | 54,2 | 0,4 |
| 463 | 0,0 | 0,0 | 514 | 55,1 | 11,6 | 565 | 53,4 | 0,0 |
| 464 | 0,0 | 1,5 | 515 | 56,8 | 5,7 | 566 | 51,4 | m |
| 465 | 0,9 | 41,1 | 516 | 42,4 | 0,0 | 567 | 48,7 | m |
| 466 | 7,0 | 46,3 | 517 | 27,9 | 8,2 | 568 | 45,6 | m |
| 467 | 12,8 | 48,5 | 518 | 29,0 | 15,9 | 569 | 42,4 | m |
| 468 | 17,0 | 50,7 | 519 | 30,4 | 25,1 | 570 | 40,4 | m |
| 469 | 20,9 | 52,9 | 520 | 32,6 | 60,5 | 571 | 39,8 | 5,8 |
| 470 | 26,7 | 55,0 | 521 | 35,4 | 72,7 | 572 | 40,7 | 39,7 |
| 471 | 35,5 | 57,2 | 522 | 38,4 | 88,2 | 573 | 43,8 | 37,1 |
| 472 | 46,9 | 23,8 | 523 | 41,0 | 65,1 | 574 | 48,1 | 39,1 |
| 473 | 44,5 | 0,0 | 524 | 42,9 | 25,6 | 575 | 52,0 | 22,0 |
| 474 | 42,1 | 45,7 | 525 | 44,2 | 15,8 | 576 | 54,7 | 13,2 |
| 475 | 55,6 | 77,4 | 526 | 44,9 | 2,9 | 577 | 56,4 | 13,2 |
| 476 | 68,8 | 100,0 | 527 | 45,1 | m | 578 | 57,5 | 6,6 |
| 477 | 81,7 | 47,9 | 528 | 44,8 | m | 579 | 42,6 | 0,0 |
| 478 | 71,2 | 0,0 | 529 | 43,9 | m | 580 | 27,7 | 10,9 |
| 479 | 60,7 | 38,3 | 530 | 42,4 | m | 581 | 28,5 | 21,3 |
| 480 | 68,8 | 72,7 | 531 | 40,2 | m | 582 | 29,2 | 23,9 |
| 481 | 75,0 | m | 532 | 37,1 | m | 583 | 29,5 | 15,2 |
| 482 | 61,3 | m | 533 | 47,0 | 0,0 | 584 | 29,7 | 8,8 |
| 483 | 53,5 | m | 534 | 57,0 | m | 585 | 30,4 | 20,8 |
| 484 | 45,9 | 58,0 | 535 | 45,1 | m | 586 | 31,9 | 22,9 |
| 485 | 48,1 | 80,0 | 536 | 32,6 | m | 587 | 34,3 | 61,4 |
| 486 | 49,4 | 97,9 | 537 | 46,8 | 0,0 | 588 | 37,2 | 76,6 |
| 487 | 49,7 | m | 538 | 61,5 | m | 589 | 40,1 | 27,5 |
| 488 | 48,7 | m | 539 | 56,7 | m | 590 | 42,3 | 25,4 |
| 489 | 45,5 | m | 540 | 46,9 | m | 591 | 43,5 | 32,0 |
| 490 | 40,4 | m | 541 | 37,5 | m | 592 | 43,8 | 6,0 |
| 491 | 49,7 | 0,0 | 542 | 30,3 | m | 593 | 43,5 | m |
| 492 | 59,0 | m | 543 | 27,3 | 32,3 | 594 | 42,8 | m |
| 493 | 48,9 | m | 544 | 30,8 | 60,3 | 595 | 41,7 | m |
| 494 | 40,0 | m | 545 | 41,2 | 62,3 | 596 | 40,4 | m |
| 495 | 33,5 | m | 546 | 36,0 | 0,0 | 597 | 39,3 | m |
| 496 | 30,0 | m | 547 | 30,8 | 32,3 | 598 | 38,9 | 12,9 |
| 497 | 29,1 | 12,0 | 548 | 33,9 | 60,3 | 599 | 39,0 | 18,4 |
| 498 | 29,3 | 40,4 | 549 | 34,6 | 38,4 | 600 | 39,7 | 39,2 |
| 499 | 30,4 | 29,3 | 550 | 37,0 | 16,6 | 601 | 41,4 | 60,0 |
| 500 | 32,2 | 15,4 | 551 | 42,7 | 62,3 | 602 | 43,7 | 54,5 |
| 501 | 33,9 | 15,8 | 552 | 50,4 | 28,1 | 603 | 46,2 | 64,2 |
| 502 | 35,3 | 14,9 | 553 | 40,1 | 0,0 | 604 | 48,8 | 73,3 |
| 503 | 36,4 | 15,1 | 554 | 29,9 | 8,0 | 605 | 51,0 | 82,3 |
| 504 | 38,0 | 15,3 | 555 | 32,5 | 15,0 | 606 | 52,1 | 0,0 |
| 505 | 40,3 | 50,9 | 556 | 34,6 | 63,1 | 607 | 52,0 | m |
| 506 | 43,0 | 39,7 | 557 | 36,7 | 58,0 | 608 | 50,9 | m |
| 507 | 45,5 | 20,6 | 558 | 39,4 | 52,9 | 609 | 49,4 | m |
| 508 | 47,3 | 20,6 | 559 | 42,8 | 47,8 | 610 | 47,8 | m |
| 509 | 48,8 | 22,1 | 560 | 46,8 | 42,7 | 611 | 46,6 | m |
| 510 | 50,1 | 22,1 | 561 | 50,7 | 27,5 | 612 | 47,3 | 35,3 |

| Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque |
|---|---|---|---|---|---|---|---|---|
| s | % | % | s | % | % | s | % | % |
| 613 | 49,2 | 74,1 | 664 | 66,9 | 0,0 | 715 | 0,0 | 0,0 |
| 614 | 51,1 | 95,2 | 665 | 60,4 | 41,8 | 716 | 0,0 | 0,0 |
| 615 | 51,7 | m | 666 | 69,1 | 79,0 | 717 | 0,0 | 0,0 |
| 616 | 50,8 | m | 667 | 77,1 | 38,3 | 718 | 0,0 | 0,0 |
| 617 | 47,3 | m | 668 | 63,1 | 0,0 | 719 | 0,0 | 0,0 |
| 618 | 41,8 | m | 669 | 49,1 | 47,9 | 720 | 0,0 | 0,0 |
| 619 | 36,4 | m | 670 | 53,4 | 91,3 | 721 | 0,0 | 0,0 |
| 620 | 30,9 | m | 671 | 57,5 | 85,7 | 722 | 0,0 | 0,0 |
| 621 | 25,5 | 37,1 | 672 | 61,5 | 89,2 | 723 | 0,0 | 0,0 |
| 622 | 33,8 | 38,4 | 673 | 65,5 | 85,9 | 724 | 0,0 | 0,0 |
| 623 | 42,1 | m | 674 | 69,5 | 89,5 | 725 | 0,0 | 0,0 |
| 624 | 34,1 | m | 675 | 73,1 | 75,5 | 726 | 0,0 | 0,0 |
| 625 | 33,0 | 37,1 | 676 | 76,2 | 73,6 | 727 | 0,0 | 0,0 |
| 626 | 36,4 | 38,4 | 677 | 79,1 | 75,6 | 728 | 0,0 | 0,0 |
| 627 | 43,3 | 17,1 | 678 | 81,8 | 78,2 | 729 | 0,0 | 0,0 |
| 628 | 35,7 | 0,0 | 679 | 84,1 | 39,0 | 730 | 0,0 | 0,0 |
| 629 | 28,1 | 11,6 | 680 | 69,6 | 0,0 | 731 | 0,0 | 0,0 |
| 630 | 36,5 | 19,2 | 681 | 55,0 | 25,2 | 732 | 0,0 | 0,0 |
| 631 | 45,2 | 8,3 | 682 | 55,8 | 49,9 | 733 | 0,0 | 0,0 |
| 632 | 36,5 | 0,0 | 683 | 56,7 | 46,4 | 734 | 0,0 | 0,0 |
| 633 | 27,9 | 32,6 | 684 | 57,6 | 76,3 | 735 | 0,0 | 0,0 |
| 634 | 31,5 | 59,6 | 685 | 58,4 | 92,7 | 736 | 0,0 | 0,0 |
| 635 | 34,4 | 65,2 | 686 | 59,3 | 99,9 | 737 | 0,0 | 0,0 |
| 636 | 37,0 | 59,6 | 687 | 60,1 | 95,0 | 738 | 0,0 | 0,0 |
| 637 | 39,0 | 49,0 | 688 | 61,0 | 46,7 | 739 | 0,0 | 0,0 |
| 638 | 40,2 | m | 689 | 46,6 | 0,0 | 740 | 0,0 | 0,0 |
| 639 | 39,8 | m | 690 | 32,3 | 34,6 | 741 | 0,0 | 0,0 |
| 640 | 36,0 | m | 691 | 32,7 | 68,6 | 742 | 0,0 | 0,0 |
| 641 | 29,7 | m | 692 | 32,6 | 67,0 | 743 | 0,0 | 0,0 |
| 642 | 21,5 | m | 693 | 31,3 | m | 744 | 0,0 | 0,0 |
| 643 | 14,1 | m | 694 | 28,1 | m | 745 | 0,0 | 0,0 |
| 644 | 0,0 | 0,0 | 695 | 43,0 | 0,0 | 746 | 0,0 | 0,0 |
| 645 | 0,0 | 0,0 | 696 | 58,0 | m | 747 | 0,0 | 0,0 |
| 646 | 0,0 | 0,0 | 697 | 58,9 | m | 748 | 0,0 | 0,0 |
| 647 | 0,0 | 0,0 | 698 | 49,4 | m | 749 | 0,0 | 0,0 |
| 648 | 0,0 | 0,0 | 699 | 41,5 | m | 750 | 0,0 | 0,0 |
| 649 | 0,0 | 0,0 | 700 | 48,4 | 0,0 | 751 | 0,0 | 0,0 |
| 650 | 0,0 | 0,0 | 701 | 55,3 | m | 752 | 0,0 | 0,0 |
| 651 | 0,0 | 0,0 | 702 | 41,8 | m | 753 | 0,0 | 0,0 |
| 652 | 0,0 | 0,0 | 703 | 31,6 | m | 754 | 0,0 | 0,0 |
| 653 | 0,0 | 0,0 | 704 | 24,6 | m | 755 | 0,0 | 0,0 |
| 654 | 0,0 | 0,0 | 705 | 15,2 | m | 756 | 0,0 | 0,0 |
| 655 | 0,0 | 0,0 | 706 | 7,0 | m | 757 | 0,0 | 0,0 |
| 656 | 0,0 | 3,4 | 707 | 0,0 | 0,0 | 758 | 0,0 | 0,0 |
| 657 | 1,4 | 22,0 | 708 | 0,0 | 0,0 | 759 | 0,0 | 0,0 |
| 658 | 10,1 | 45,3 | 709 | 0,0 | 0,0 | 760 | 0,0 | 0,0 |
| 659 | 21,5 | 10,0 | 710 | 0,0 | 0,0 | 761 | 0,0 | 0,0 |
| 660 | 32,2 | 0,0 | 711 | 0,0 | 0,0 | 762 | 0,0 | 0,0 |
| 661 | 42,3 | 46,0 | 712 | 0,0 | 0,0 | 763 | 0,0 | 0,0 |
| 662 | 57,1 | 74,1 | 713 | 0,0 | 0,0 | 764 | 0,0 | 0,0 |
| 663 | 72,1 | 34,2 | 714 | 0,0 | 0,0 | 765 | 0,0 | 0,0 |

| Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque |
|------|-------|--------|------|-------|--------|------|-------|--------|
| s | % | % | s | % | % | s | % | % |
| 766 | 0,0 | 0,0 | 817 | 50,6 | 62,1 | 868 | 37,0 | m |
| 767 | 0,0 | 0,0 | 818 | 52,3 | 62,9 | 869 | 36,6 | m |
| 768 | 0,0 | 0,0 | 819 | 54,8 | 37,5 | 870 | 36,0 | m |
| 769 | 0,0 | 0,0 | 820 | 57,0 | 18,3 | 871 | 35,4 | m |
| 770 | 0,0 | 0,0 | 821 | 42,3 | 0,0 | 872 | 34,7 | m |
| 771 | 0,0 | 22,0 | 822 | 27,6 | 29,1 | 873 | 34,1 | m |
| 772 | 4,5 | 25,8 | 823 | 28,4 | 57,0 | 874 | 33,6 | m |
| 773 | 15,5 | 42,8 | 824 | 29,1 | 51,8 | 875 | 33,3 | m |
| 774 | 30,5 | 46,8 | 825 | 29,6 | 35,3 | 876 | 33,1 | m |
| 775 | 45,5 | 29,3 | 826 | 29,7 | 33,3 | 877 | 32,7 | m |
| 776 | 49,2 | 13,6 | 827 | 29,8 | 17,7 | 878 | 31,4 | m |
| 777 | 39,5 | 0,0 | 828 | 29,5 | m | 879 | 45,0 | 0,0 |
| 778 | 29,7 | 15,1 | 829 | 28,9 | m | 880 | 58,5 | m |
| 779 | 34,8 | 26,9 | 830 | 43,0 | 0,0 | 881 | 53,7 | m |
| 780 | 40,0 | 13,6 | 831 | 57,1 | m | 882 | 47,5 | m |
| 781 | 42,2 | m | 832 | 57,7 | m | 883 | 40,6 | m |
| 782 | 42,1 | m | 833 | 56,0 | m | 884 | 34,1 | m |
| 783 | 40,8 | m | 834 | 53,8 | m | 885 | 45,3 | 0,0 |
| 784 | 37,7 | 37,6 | 835 | 51,2 | m | 886 | 56,4 | m |
| 785 | 47,0 | 35,0 | 836 | 48,1 | m | 887 | 51,0 | m |
| 786 | 48,8 | 33,4 | 837 | 44,5 | m | 888 | 44,5 | m |
| 787 | 41,7 | m | 838 | 40,9 | m | 889 | 36,4 | m |
| 788 | 27,7 | m | 839 | 38,1 | m | 890 | 26,6 | m |
| 789 | 17,2 | m | 840 | 37,2 | 42,7 | 891 | 20,0 | m |
| 790 | 14,0 | 37,6 | 841 | 37,5 | 70,8 | 892 | 13,3 | m |
| 791 | 18,4 | 25,0 | 842 | 39,1 | 48,6 | 893 | 6,7 | m |
| 792 | 27,6 | 17,7 | 843 | 41,3 | 0,1 | 894 | 0,0 | 0,0 |
| 793 | 39,8 | 6,8 | 844 | 42,3 | m | 895 | 0,0 | 0,0 |
| 794 | 34,3 | 0,0 | 845 | 42,0 | m | 896 | 0,0 | 0,0 |
| 795 | 28,7 | 26,5 | 846 | 40,8 | m | 897 | 0,0 | 0,0 |
| 796 | 41,5 | 40,9 | 847 | 38,6 | m | 898 | 0,0 | 0,0 |
| 797 | 53,7 | 17,5 | 848 | 35,5 | m | 899 | 0,0 | 0,0 |
| 798 | 42,4 | 0,0 | 849 | 32,1 | m | 900 | 0,0 | 0,0 |
| 799 | 31,2 | 27,3 | 850 | 29,6 | m | 901 | 0,0 | 5,8 |
| 800 | 32,3 | 53,2 | 851 | 28,8 | 39,9 | 902 | 2,5 | 27,9 |
| 801 | 34,5 | 60,6 | 852 | 29,2 | 52,9 | 903 | 12,4 | 29,0 |
| 802 | 37,6 | 68,0 | 853 | 30,9 | 76,1 | 904 | 19,4 | 30,1 |
| 803 | 41,2 | 75,4 | 854 | 34,3 | 76,5 | 905 | 29,3 | 31,2 |
| 804 | 45,8 | 82,8 | 855 | 38,3 | 75,5 | 906 | 37,1 | 10,4 |
| 805 | 52,3 | 38,2 | 856 | 42,5 | 74,8 | 907 | 40,6 | 4,9 |
| 806 | 42,5 | 0,0 | 857 | 46,6 | 74,2 | 908 | 35,8 | 0,0 |
| 807 | 32,6 | 30,5 | 858 | 50,7 | 76,2 | 909 | 30,9 | 7,6 |
| 808 | 35,0 | 57,9 | 859 | 54,8 | 75,1 | 910 | 35,4 | 13,8 |
| 809 | 36,0 | 77,3 | 860 | 58,7 | 36,3 | 911 | 36,5 | 11,1 |
| 810 | 37,1 | 96,8 | 861 | 45,2 | 0,0 | 912 | 40,8 | 48,5 |
| 811 | 39,6 | 80,8 | 862 | 31,8 | 37,2 | 913 | 49,8 | 3,7 |
| 812 | 43,4 | 78,3 | 863 | 33,8 | 71,2 | 914 | 41,2 | 0,0 |
| 813 | 47,2 | 73,4 | 864 | 35,5 | 46,4 | 915 | 32,7 | 29,7 |
| 814 | 49,6 | 66,9 | 865 | 36,6 | 33,6 | 916 | 39,4 | 52,1 |
| 815 | 50,2 | 62,0 | 866 | 37,2 | 20,0 | 917 | 48,8 | 22,7 |
| 816 | 50,2 | 57,7 | 867 | 37,2 | m | 918 | 41,6 | 0,0 |

| Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque |
|------|-------|--------|------|-------|--------|------|-------|--------|
| s | % | % | s | % | % | s | % | % |
| 919 | 34,5 | 46,6 | 970 | 35,4 | 30,2 | 1021 | 52,5 | 13,1 |
| 920 | 39,7 | 84,4 | 971 | 36,6 | 55,6 | 1022 | 56,2 | 6,3 |
| 921 | 44,7 | 83,2 | 972 | 38,6 | 48,5 | 1023 | 44,0 | 0,0 |
| 922 | 49,5 | 78,9 | 973 | 39,9 | 41,8 | 1024 | 31,8 | 20,9 |
| 923 | 52,3 | 83,8 | 974 | 40,3 | 38,2 | 1025 | 38,7 | 36,3 |
| 924 | 53,4 | 77,7 | 975 | 40,8 | 35,0 | 1026 | 47,7 | 47,5 |
| 925 | 52,1 | 69,6 | 976 | 41,9 | 32,4 | 1027 | 54,5 | 22,0 |
| 926 | 47,9 | 63,6 | 977 | 43,2 | 26,4 | 1028 | 41,3 | 0,0 |
| 927 | 46,4 | 55,2 | 978 | 43,5 | m | 1029 | 28,1 | 26,8 |
| 928 | 46,5 | 53,6 | 979 | 42,9 | m | 1030 | 31,6 | 49,2 |
| 929 | 46,4 | 62,3 | 980 | 41,5 | m | 1031 | 34,5 | 39,5 |
| 930 | 46,1 | 58,2 | 981 | 40,9 | m | 1032 | 36,4 | 24,0 |
| 931 | 46,2 | 61,8 | 982 | 40,5 | m | 1033 | 36,7 | m |
| 932 | 47,3 | 62,3 | 983 | 39,5 | m | 1034 | 35,5 | m |
| 933 | 49,3 | 57,1 | 984 | 38,3 | m | 1035 | 33,8 | m |
| 934 | 52,6 | 58,1 | 985 | 36,9 | m | 1036 | 33,7 | 19,8 |
| 935 | 56,3 | 56,0 | 986 | 35,4 | m | 1037 | 35,3 | 35,1 |
| 936 | 59,9 | 27,2 | 987 | 34,5 | m | 1038 | 38,0 | 33,9 |
| 937 | 45,8 | 0,0 | 988 | 33,9 | m | 1039 | 40,1 | 34,5 |
| 938 | 31,8 | 28,8 | 989 | 32,6 | m | 1040 | 42,2 | 40,4 |
| 939 | 32,7 | 56,5 | 990 | 30,9 | m | 1041 | 45,2 | 44,0 |
| 940 | 33,4 | 62,8 | 991 | 29,9 | m | 1042 | 48,3 | 35,9 |
| 941 | 34,6 | 68,2 | 992 | 29,2 | m | 1043 | 50,1 | 29,6 |
| 942 | 35,8 | 68,6 | 993 | 44,1 | 0,0 | 1044 | 52,3 | 38,5 |
| 943 | 38,6 | 65,0 | 994 | 59,1 | m | 1045 | 55,3 | 57,7 |
| 944 | 42,3 | 61,9 | 995 | 56,8 | m | 1046 | 57,0 | 50,7 |
| 945 | 44,1 | 65,3 | 996 | 53,5 | m | 1047 | 57,7 | 25,2 |
| 946 | 45,3 | 63,2 | 997 | 47,8 | m | 1048 | 42,9 | 0,0 |
| 947 | 46,5 | 30,6 | 998 | 41,9 | m | 1049 | 28,2 | 15,7 |
| 948 | 46,7 | 11,1 | 999 | 35,9 | m | 1050 | 29,2 | 30,5 |
| 949 | 45,9 | 16,1 | 1000 | 44,3 | 0,0 | 1051 | 31,1 | 52,6 |
| 950 | 45,6 | 21,8 | 1001 | 52,6 | m | 1052 | 33,4 | 60,7 |
| 951 | 45,9 | 24,2 | 1002 | 43,4 | m | 1053 | 35,0 | 61,4 |
| 952 | 46,5 | 24,7 | 1003 | 50,6 | 0,0 | 1054 | 35,3 | 18,2 |
| 953 | 46,7 | 24,7 | 1004 | 57,8 | m | 1055 | 35,2 | 14,9 |
| 954 | 46,8 | 28,2 | 1005 | 51,6 | m | 1056 | 34,9 | 11,7 |
| 955 | 47,2 | 31,2 | 1006 | 44,8 | m | 1057 | 34,5 | 12,9 |
| 956 | 47,6 | 29,6 | 1007 | 48,6 | 0,0 | 1058 | 34,1 | 15,5 |
| 957 | 48,2 | 31,2 | 1008 | 52,4 | m | 1059 | 33,5 | m |
| 958 | 48,6 | 33,5 | 1009 | 45,4 | m | 1060 | 31,8 | m |
| 959 | 48,8 | m | 1010 | 37,2 | m | 1061 | 30,1 | m |
| 960 | 47,6 | m | 1011 | 26,3 | m | 1062 | 29,6 | 10,3 |
| 961 | 46,3 | m | 1012 | 17,9 | m | 1063 | 30,0 | 26,5 |
| 962 | 45,2 | m | 1013 | 16,2 | 1,9 | 1064 | 31,0 | 18,8 |
| 963 | 43,5 | m | 1014 | 17,8 | 7,5 | 1065 | 31,5 | 26,5 |
| 964 | 41,4 | m | 1015 | 25,2 | 18,0 | 1066 | 31,7 | m |
| 965 | 40,3 | m | 1016 | 39,7 | 6,5 | 1067 | 31,5 | m |
| 966 | 39,4 | m | 1017 | 38,6 | 0,0 | 1068 | 30,6 | m |
| 967 | 38,0 | m | 1018 | 37,4 | 5,4 | 1069 | 30,0 | m |
| 968 | 36,3 | m | 1019 | 43,4 | 9,7 | 1070 | 30,0 | m |
| 969 | 35,3 | 5,8 | 1020 | 46,9 | 15,7 | 1071 | 29,4 | m |

| Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque |
|------|------|------|------|------|------|------|------|------|
| s | % | % | s | % | % | s | % | % |
| 1072 | 44,3 | 0,0 | 1123 | 31,0 | 12,4 | 1174 | 0,0 | 0,0 |
| 1073 | 59,2 | m | 1124 | 30,1 | 18,5 | 1175 | 0,0 | 0,0 |
| 1074 | 58,3 | m | 1125 | 30,4 | 35,6 | 1176 | 0,0 | 0,0 |
| 1075 | 57,1 | m | 1126 | 31,2 | 30,1 | 1177 | 0,0 | 0,0 |
| 1076 | 55,4 | m | 1127 | 31,5 | 30,8 | 1178 | 0,0 | 0,0 |
| 1077 | 53,5 | m | 1128 | 31,5 | 26,9 | 1179 | 0,0 | 0,0 |
| 1078 | 51,5 | m | 1129 | 31,7 | 33,9 | 1180 | 0,0 | 0,0 |
| 1079 | 49,7 | m | 1130 | 32,0 | 29,9 | 1181 | 0,0 | 0,0 |
| 1080 | 47,9 | m | 1131 | 32,1 | m | 1182 | 0,0 | 0,0 |
| 1081 | 46,4 | m | 1132 | 31,4 | m | 1183 | 0,0 | 0,0 |
| 1082 | 45,5 | m | 1133 | 30,3 | m | 1184 | 0,0 | 0,0 |
| 1083 | 45,2 | m | 1134 | 29,8 | m | 1185 | 0,0 | 0,0 |
| 1084 | 44,3 | m | 1135 | 44,3 | 0,0 | 1186 | 0,0 | 0,0 |
| 1085 | 43,6 | m | 1136 | 58,9 | m | 1187 | 0,0 | 0,0 |
| 1086 | 43,1 | m | 1137 | 52,1 | m | 1188 | 0,0 | 0,0 |
| 1087 | 42,5 | 25,6 | 1138 | 44,1 | m | 1189 | 0,0 | 0,0 |
| 1088 | 43,3 | 25,7 | 1139 | 51,7 | 0,0 | 1190 | 0,0 | 0,0 |
| 1089 | 46,3 | 24,0 | 1140 | 59,2 | m | 1191 | 0,0 | 0,0 |
| 1090 | 47,8 | 20,6 | 1141 | 47,2 | m | 1192 | 0,0 | 0,0 |
| 1091 | 47,2 | 3,8 | 1142 | 35,1 | 0,0 | 1193 | 0,0 | 0,0 |
| 1092 | 45,6 | 4,4 | 1143 | 23,1 | m | 1194 | 0,0 | 0,0 |
| 1093 | 44,6 | 4,1 | 1144 | 13,1 | m | 1195 | 0,0 | 0,0 |
| 1094 | 44,1 | m | 1145 | 5,0 | m | 1196 | 0,0 | 20,4 |
| 1095 | 42,9 | m | 1146 | 0,0 | 0,0 | 1197 | 12,6 | 41,2 |
| 1096 | 40,9 | m | 1147 | 0,0 | 0,0 | 1198 | 27,3 | 20,4 |
| 1097 | 39,2 | m | 1148 | 0,0 | 0,0 | 1199 | 40,4 | 7,6 |
| 1098 | 37,0 | m | 1149 | 0,0 | 0,0 | 1200 | 46,1 | m |
| 1099 | 35,1 | 2,0 | 1150 | 0,0 | 0,0 | 1201 | 44,6 | m |
| 1100 | 35,6 | 43,3 | 1151 | 0,0 | 0,0 | 1202 | 42,7 | 14,7 |
| 1101 | 38,7 | 47,6 | 1152 | 0,0 | 0,0 | 1203 | 42,9 | 7,3 |
| 1102 | 41,3 | 40,4 | 1153 | 0,0 | 0,0 | 1204 | 36,1 | 0,0 |
| 1103 | 42,6 | 45,7 | 1154 | 0,0 | 0,0 | 1205 | 29,3 | 15,0 |
| 1104 | 43,9 | 43,3 | 1155 | 0,0 | 0,0 | 1206 | 43,8 | 22,6 |
| 1105 | 46,9 | 41,2 | 1156 | 0,0 | 0,0 | 1207 | 54,9 | 9,9 |
| 1106 | 52,4 | 40,1 | 1157 | 0,0 | 0,0 | 1208 | 44,9 | 0,0 |
| 1107 | 56,3 | 39,3 | 1158 | 0,0 | 0,0 | 1209 | 34,9 | 47,4 |
| 1108 | 57,4 | 25,5 | 1159 | 0,0 | 0,0 | 1210 | 42,7 | 82,7 |
| 1109 | 57,2 | 25,4 | 1160 | 0,0 | 0,0 | 1211 | 52,0 | 81,2 |
| 1110 | 57,0 | 25,4 | 1161 | 0,0 | 0,0 | 1212 | 61,8 | 82,7 |
| 1111 | 56,8 | 25,3 | 1162 | 0,0 | 0,0 | 1213 | 71,3 | 39,1 |
| 1112 | 56,3 | 25,3 | 1163 | 0,0 | 0,0 | 1214 | 58,1 | 0,0 |
| 1113 | 55,6 | 25,2 | 1164 | 0,0 | 0,0 | 1215 | 44,9 | 42,5 |
| 1114 | 56,2 | 25,2 | 1165 | 0,0 | 0,0 | 1216 | 46,3 | 83,3 |
| 1115 | 58,0 | 12,4 | 1166 | 0,0 | 0,0 | 1217 | 46,8 | 74,1 |
| 1116 | 43,4 | 0,0 | 1167 | 0,0 | 0,0 | 1218 | 48,1 | 75,7 |
| 1117 | 28,8 | 26,2 | 1168 | 0,0 | 0,0 | 1219 | 50,5 | 75,8 |
| 1118 | 30,9 | 49,9 | 1169 | 0,0 | 0,0 | 1220 | 53,6 | 76,7 |
| 1119 | 32,3 | 40,5 | 1170 | 0,0 | 0,0 | 1221 | 56,9 | 77,1 |
| 1120 | 32,5 | 12,4 | 1171 | 0,0 | 0,0 | 1222 | 60,2 | 78,7 |
| 1121 | 32,4 | 12,2 | 1172 | 0,0 | 0,0 | 1223 | 63,7 | 78,0 |
| 1122 | 32,1 | 6,4 | 1173 | 0,0 | 0,0 | 1224 | 67,2 | 79,6 |

| Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque |
|---|---|---|---|---|---|---|---|---|
| s | % | % | s | % | % | s | % | % |
| 1225 | 70,7 | 80,9 | 1276 | 42,3 | m | 1327 | 37,6 | 57,8 |
| 1226 | 74,1 | 81,1 | 1277 | 41,0 | m | 1328 | 37,3 | 73,2 |
| 1227 | 77,5 | 83,6 | 1278 | 39,6 | m | 1329 | 37,3 | 59,8 |
| 1228 | 80,8 | 85,6 | 1279 | 38,3 | m | 1330 | 37,4 | 52,2 |
| 1229 | 84,1 | 81,6 | 1280 | 37,1 | m | 1331 | 37,4 | 16,9 |
| 1230 | 87,4 | 88,3 | 1281 | 35,9 | m | 1332 | 37,1 | 34,3 |
| 1231 | 90,5 | 91,9 | 1282 | 34,6 | m | 1333 | 36,7 | 51,9 |
| 1232 | 93,5 | 94,1 | 1283 | 33,0 | m | 1334 | 36,2 | 25,3 |
| 1233 | 96,8 | 96,6 | 1284 | 31,1 | m | 1335 | 35,6 | m |
| 1234 | 100,0 | m | 1285 | 29,2 | m | 1336 | 34,6 | m |
| 1235 | 96,0 | m | 1286 | 43,3 | 0,0 | 1337 | 33,2 | m |
| 1236 | 81,9 | m | 1287 | 57,4 | 32,8 | 1338 | 31,6 | m |
| 1237 | 68,1 | m | 1288 | 59,9 | 65,4 | 1339 | 30,1 | m |
| 1238 | 58,1 | 84,7 | 1289 | 61,9 | 76,1 | 1340 | 28,8 | m |
| 1239 | 58,5 | 85,4 | 1290 | 65,6 | 73,7 | 1341 | 28,0 | 29,5 |
| 1240 | 59,5 | 85,6 | 1291 | 69,9 | 79,3 | 1342 | 28,6 | 100,0 |
| 1241 | 61,0 | 86,6 | 1292 | 74,1 | 81,3 | 1343 | 28,8 | 97,3 |
| 1242 | 62,6 | 86,8 | 1293 | 78,3 | 83,2 | 1344 | 28,8 | 73,4 |
| 1243 | 64,1 | 87,6 | 1294 | 82,6 | 86,0 | 1345 | 29,6 | 56,9 |
| 1244 | 65,4 | 87,5 | 1295 | 87,0 | 89,5 | 1346 | 30,3 | 91,7 |
| 1245 | 66,7 | 87,8 | 1296 | 91,2 | 90,8 | 1347 | 31,0 | 90,5 |
| 1246 | 68,1 | 43,5 | 1297 | 95,3 | 45,9 | 1348 | 31,8 | 81,7 |
| 1247 | 55,2 | 0,0 | 1298 | 81,0 | 0,0 | 1349 | 32,6 | 79,5 |
| 1248 | 42,3 | 37,2 | 1299 | 66,6 | 38,2 | 1350 | 33,5 | 86,9 |
| 1249 | 43,0 | 73,6 | 1300 | 67,9 | 75,5 | 1351 | 34,6 | 100,0 |
| 1250 | 43,5 | 65,1 | 1301 | 68,4 | 80,5 | 1352 | 35,6 | 78,7 |
| 1251 | 43,8 | 53,1 | 1302 | 69,0 | 85,5 | 1353 | 36,4 | 50,5 |
| 1252 | 43,9 | 54,6 | 1303 | 70,0 | 85,2 | 1354 | 37,0 | 57,0 |
| 1253 | 43,9 | 41,2 | 1304 | 71,6 | 85,9 | 1355 | 37,3 | 69,1 |
| 1254 | 43,8 | 34,8 | 1305 | 73,3 | 86,2 | 1356 | 37,6 | 49,5 |
| 1255 | 43,6 | 30,3 | 1306 | 74,8 | 86,5 | 1357 | 37,8 | 44,4 |
| 1256 | 43,3 | 21,9 | 1307 | 76,3 | 42,9 | 1358 | 37,8 | 43,4 |
| 1257 | 42,8 | 19,9 | 1308 | 63,3 | 0,0 | 1359 | 37,8 | 34,8 |
| 1258 | 42,3 | m | 1309 | 50,4 | 21,2 | 1360 | 37,6 | 24,0 |
| 1259 | 41,4 | m | 1310 | 50,6 | 42,3 | 1361 | 37,2 | m |
| 1260 | 40,2 | m | 1311 | 50,6 | 53,7 | 1362 | 36,3 | m |
| 1261 | 38,7 | m | 1312 | 50,4 | 90,1 | 1363 | 35,1 | m |
| 1262 | 37,1 | m | 1313 | 50,5 | 97,1 | 1364 | 33,7 | m |
| 1263 | 35,6 | m | 1314 | 51,0 | 100,0 | 1365 | 32,4 | m |
| 1264 | 34,2 | m | 1315 | 51,9 | 100,0 | 1366 | 31,1 | m |
| 1265 | 32,9 | m | 1316 | 52,6 | 100,0 | 1367 | 29,9 | m |
| 1266 | 31,8 | m | 1317 | 52,8 | 32,4 | 1368 | 28,7 | m |
| 1267 | 30,7 | m | 1318 | 47,7 | 0,0 | 1369 | 29,0 | 58,6 |
| 1268 | 29,6 | m | 1319 | 42,6 | 27,4 | 1370 | 29,7 | 88,5 |
| 1269 | 40,4 | 0,0 | 1320 | 42,1 | 53,5 | 1371 | 31,0 | 86,3 |
| 1270 | 51,2 | m | 1321 | 41,8 | 44,5 | 1372 | 31,8 | 43,4 |
| 1271 | 49,6 | m | 1322 | 41,4 | 41,1 | 1373 | 31,7 | m |
| 1272 | 48,0 | m | 1323 | 41,0 | 21,0 | 1374 | 29,9 | m |
| 1273 | 46,4 | m | 1324 | 40,3 | 0,0 | 1375 | 40,2 | 0,0 |
| 1274 | 45,0 | m | 1325 | 39,3 | 1,0 | 1376 | 50,4 | m |
| 1275 | 43,6 | m | 1326 | 38,3 | 15,2 | 1377 | 47,9 | m |

| Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque |
|------|------|------|------|------|------|------|------|------|
| s | % | % | s | % | % | s | % | % |
| 1378 | 45,0 | m | 1429 | 52,7 | 37,2 | 1480 | 56,1 | 94,9 |
| 1379 | 43,0 | m | 1430 | 41,6 | 0,0 | 1481 | 56,3 | 86,2 |
| 1380 | 40,6 | m | 1431 | 30,4 | 36,6 | 1482 | 56,2 | 64,1 |
| 1381 | 55,5 | 0,0 | 1432 | 30,5 | 73,2 | 1483 | 56,0 | 46,1 |
| 1382 | 70,4 | 41,7 | 1433 | 30,3 | 81,6 | 1484 | 56,2 | 33,4 |
| 1383 | 73,4 | 83,2 | 1434 | 30,4 | 89,3 | 1485 | 56,5 | 23,6 |
| 1384 | 74,0 | 83,7 | 1435 | 31,5 | 90,4 | 1486 | 56,3 | 18,6 |
| 1385 | 74,9 | 41,7 | 1436 | 32,7 | 88,5 | 1487 | 55,7 | 16,2 |
| 1386 | 60,0 | 0,0 | 1437 | 33,7 | 97,2 | 1488 | 56,0 | 15,9 |
| 1387 | 45,1 | 41,6 | 1438 | 35,2 | 99,7 | 1489 | 55,9 | 21,8 |
| 1388 | 47,7 | 84,2 | 1439 | 36,3 | 98,8 | 1490 | 55,8 | 20,9 |
| 1389 | 50,4 | 50,2 | 1440 | 37,7 | 100,0 | 1491 | 55,4 | 18,4 |
| 1390 | 53,0 | 26,1 | 1441 | 39,2 | 100,0 | 1492 | 55,7 | 25,1 |
| 1391 | 59,5 | 0,0 | 1442 | 40,9 | 100,0 | 1493 | 56,0 | 27,7 |
| 1392 | 66,2 | 38,4 | 1443 | 42,4 | 99,5 | 1494 | 55,8 | 22,4 |
| 1393 | 66,4 | 76,7 | 1444 | 43,8 | 98,7 | 1495 | 56,1 | 20,0 |
| 1394 | 67,6 | 100,0 | 1445 | 45,4 | 97,3 | 1496 | 55,7 | 17,4 |
| 1395 | 68,4 | 76,6 | 1446 | 47,0 | 96,6 | 1497 | 55,9 | 20,9 |
| 1396 | 68,2 | 47,2 | 1447 | 47,8 | 96,2 | 1498 | 56,0 | 22,9 |
| 1397 | 69,0 | 81,4 | 1448 | 48,8 | 96,3 | 1499 | 56,0 | 21,1 |
| 1398 | 69,7 | 40,6 | 1449 | 50,5 | 95,1 | 1500 | 55,1 | 19,2 |
| 1399 | 54,7 | 0,0 | 1450 | 51,0 | 95,9 | 1501 | 55,6 | 24,2 |
| 1400 | 39,8 | 19,9 | 1451 | 52,0 | 94,3 | 1502 | 55,4 | 25,6 |
| 1401 | 36,3 | 40,0 | 1452 | 52,6 | 94,6 | 1503 | 55,7 | 24,7 |
| 1402 | 36,7 | 59,4 | 1453 | 53,0 | 65,5 | 1504 | 55,9 | 24,0 |
| 1403 | 36,6 | 77,5 | 1454 | 53,2 | 0,0 | 1505 | 55,4 | 23,5 |
| 1404 | 36,8 | 94,3 | 1455 | 53,2 | m | 1506 | 55,7 | 30,9 |
| 1405 | 36,8 | 100,0 | 1456 | 52,6 | m | 1507 | 55,4 | 42,5 |
| 1406 | 36,4 | 100,0 | 1457 | 52,1 | m | 1508 | 55,3 | 25,8 |
| 1407 | 36,3 | 79,7 | 1458 | 51,8 | m | 1509 | 55,4 | 1,3 |
| 1408 | 36,7 | 49,5 | 1459 | 51,3 | m | 1510 | 55,0 | m |
| 1409 | 36,6 | 39,3 | 1460 | 50,7 | m | 1511 | 54,4 | m |
| 1410 | 37,3 | 62,8 | 1461 | 50,7 | m | 1512 | 54,2 | m |
| 1411 | 38,1 | 73,4 | 1462 | 49,8 | m | 1513 | 53,5 | m |
| 1412 | 39,0 | 72,9 | 1463 | 49,4 | m | 1514 | 52,4 | m |
| 1413 | 40,2 | 72,0 | 1464 | 49,3 | m | 1515 | 51,8 | m |
| 1414 | 41,5 | 71,2 | 1465 | 49,1 | m | 1516 | 50,7 | m |
| 1415 | 42,9 | 77,3 | 1466 | 49,1 | m | 1517 | 49,9 | m |
| 1416 | 44,4 | 76,6 | 1467 | 49,1 | 8,3 | 1518 | 49,1 | m |
| 1417 | 45,4 | 43,1 | 1468 | 48,9 | 16,8 | 1519 | 47,7 | m |
| 1418 | 45,3 | 53,9 | 1469 | 48,8 | 21,3 | 1520 | 47,3 | m |
| 1419 | 45,1 | 64,8 | 1470 | 49,1 | 22,1 | 1521 | 46,9 | m |
| 1420 | 46,5 | 74,2 | 1471 | 49,4 | 26,3 | 1522 | 46,9 | m |
| 1421 | 47,7 | 75,2 | 1472 | 49,8 | 39,2 | 1523 | 47,2 | m |
| 1422 | 48,1 | 75,5 | 1473 | 50,4 | 83,4 | 1524 | 47,8 | m |
| 1423 | 48,6 | 75,8 | 1474 | 51,4 | 90,6 | 1525 | 48,2 | 0,0 |
| 1424 | 48,9 | 76,3 | 1475 | 52,3 | 93,8 | 1526 | 48,8 | 23,0 |
| 1425 | 49,9 | 75,5 | 1476 | 53,3 | 94,0 | 1527 | 49,1 | 67,9 |
| 1426 | 50,4 | 75,2 | 1477 | 54,2 | 94,1 | 1528 | 49,4 | 73,7 |
| 1427 | 51,1 | 74,6 | 1478 | 54,9 | 94,3 | 1529 | 49,8 | 75,0 |
| 1428 | 51,9 | 75,0 | 1479 | 55,7 | 94,6 | 1530 | 50,4 | 75,8 |

| Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque |
|---|---|---|---|---|---|---|---|---|
| s | % | % | s | % | % | s | % | % |
| 1531 | 51,4 | 73,9 | 1582 | 56,4 | 48,9 | 1633 | 56,6 | 45,2 |
| 1532 | 52,3 | 72,2 | 1583 | 56,4 | 48,2 | 1634 | 56,8 | 46,0 |
| 1533 | 53,3 | 71,2 | 1584 | 56,5 | 48,3 | 1635 | 56,5 | 46,6 |
| 1534 | 54,6 | 71,2 | 1585 | 56,5 | 47,9 | 1636 | 56,6 | 48,3 |
| 1535 | 55,4 | 68,7 | 1586 | 56,6 | 46,8 | 1637 | 56,4 | 48,6 |
| 1536 | 56,7 | 67,0 | 1587 | 56,6 | 46,2 | 1638 | 56,6 | 50,3 |
| 1537 | 57,2 | 64,6 | 1588 | 56,5 | 44,4 | 1639 | 56,3 | 51,9 |
| 1538 | 57,3 | 61,9 | 1589 | 56,8 | 42,9 | 1640 | 56,5 | 54,1 |
| 1539 | 57,0 | 59,5 | 1590 | 56,5 | 42,8 | 1641 | 56,3 | 54,9 |
| 1540 | 56,7 | 57,0 | 1591 | 56,7 | 43,2 | 1642 | 56,4 | 55,0 |
| 1541 | 56,7 | 69,8 | 1592 | 56,5 | 42,8 | 1643 | 56,4 | 56,2 |
| 1542 | 56,8 | 58,5 | 1593 | 56,9 | 42,2 | 1644 | 56,2 | 58,6 |
| 1543 | 56,8 | 47,2 | 1594 | 56,5 | 43,1 | 1645 | 56,2 | 59,1 |
| 1544 | 57,0 | 38,5 | 1595 | 56,5 | 42,9 | 1646 | 56,2 | 62,5 |
| 1545 | 57,0 | 32,8 | 1596 | 56,7 | 42,7 | 1647 | 56,4 | 62,8 |
| 1546 | 56,8 | 30,2 | 1597 | 56,6 | 41,5 | 1648 | 56,0 | 64,7 |
| 1547 | 57,0 | 27,0 | 1598 | 56,9 | 41,8 | 1649 | 56,4 | 65,6 |
| 1548 | 56,9 | 26,2 | 1599 | 56,6 | 41,9 | 1650 | 56,2 | 67,7 |
| 1549 | 56,7 | 26,2 | 1600 | 56,7 | 42,6 | 1651 | 55,9 | 68,9 |
| 1550 | 57,0 | 26,6 | 1601 | 56,7 | 42,6 | 1652 | 56,1 | 68,9 |
| 1551 | 56,7 | 27,8 | 1602 | 56,7 | 41,5 | 1653 | 55,8 | 69,5 |
| 1552 | 56,7 | 29,7 | 1603 | 56,7 | 42,2 | 1654 | 56,0 | 69,8 |
| 1553 | 56,8 | 32,1 | 1604 | 56,5 | 42,2 | 1655 | 56,2 | 69,3 |
| 1554 | 56,5 | 34,9 | 1605 | 56,8 | 41,9 | 1656 | 56,2 | 69,8 |
| 1555 | 56,6 | 34,9 | 1606 | 56,5 | 42,0 | 1657 | 56,4 | 69,2 |
| 1556 | 56,3 | 35,8 | 1607 | 56,7 | 42,1 | 1658 | 56,3 | 68,7 |
| 1557 | 56,6 | 36,6 | 1608 | 56,4 | 41,9 | 1659 | 56,2 | 69,4 |
| 1558 | 56,2 | 37,6 | 1609 | 56,7 | 42,9 | 1660 | 56,2 | 69,5 |
| 1559 | 56,6 | 38,2 | 1610 | 56,7 | 41,8 | 1661 | 56,2 | 70,0 |
| 1560 | 56,2 | 37,9 | 1611 | 56,7 | 41,9 | 1662 | 56,4 | 69,7 |
| 1561 | 56,6 | 37,5 | 1612 | 56,8 | 42,0 | 1663 | 56,2 | 70,2 |
| 1562 | 56,4 | 36,7 | 1613 | 56,7 | 41,5 | 1664 | 56,4 | 70,5 |
| 1563 | 56,5 | 34,8 | 1614 | 56,6 | 41,9 | 1665 | 56,1 | 70,5 |
| 1564 | 56,5 | 35,8 | 1615 | 56,8 | 41,6 | 1666 | 56,5 | 69,7 |
| 1565 | 56,5 | 36,2 | 1616 | 56,6 | 41,6 | 1667 | 56,2 | 69,3 |
| 1566 | 56,5 | 36,7 | 1617 | 56,9 | 42,0 | 1668 | 56,5 | 70,9 |
| 1567 | 56,7 | 37,8 | 1618 | 56,7 | 40,7 | 1669 | 56,4 | 70,8 |
| 1568 | 56,7 | 37,8 | 1619 | 56,7 | 39,3 | 1670 | 56,3 | 71,1 |
| 1569 | 56,6 | 36,6 | 1620 | 56,5 | 41,4 | 1671 | 56,4 | 71,0 |
| 1570 | 56,8 | 36,1 | 1621 | 56,4 | 44,9 | 1672 | 56,7 | 68,6 |
| 1571 | 56,5 | 36,8 | 1622 | 56,8 | 45,2 | 1673 | 56,8 | 68,6 |
| 1572 | 56,9 | 35,9 | 1623 | 56,6 | 43,6 | 1674 | 56,6 | 68,0 |
| 1573 | 56,7 | 35,0 | 1624 | 56,8 | 42,2 | 1675 | 56,8 | 65,1 |
| 1574 | 56,5 | 36,0 | 1625 | 56,5 | 42,3 | 1676 | 56,9 | 60,9 |
| 1575 | 56,4 | 36,5 | 1626 | 56,5 | 44,4 | 1677 | 57,1 | 57,4 |
| 1576 | 56,5 | 38,0 | 1627 | 56,9 | 45,1 | 1678 | 57,1 | 54,3 |
| 1577 | 56,5 | 39,9 | 1628 | 56,4 | 45,0 | 1679 | 57,0 | 48,6 |
| 1578 | 56,4 | 42,1 | 1629 | 56,7 | 46,3 | 1680 | 57,4 | 44,1 |
| 1579 | 56,5 | 47,0 | 1630 | 56,7 | 45,5 | 1681 | 57,4 | 40,2 |
| 1580 | 56,4 | 48,0 | 1631 | 56,8 | 45,0 | 1682 | 57,6 | 36,9 |
| 1581 | 56,1 | 49,1 | 1632 | 56,7 | 44,9 | 1683 | 57,5 | 34,2 |

| Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque | Time | Norm. Speed | Norm. Torque |
|---|---|---|---|---|---|---|---|---|
| s | % | % | s | % | % | s | % | % |
| 1684 | 57,4 | 31,1 | 1735 | 55,8 | 49,3 | 1786 | 31,6 | m |
| 1685 | 57,5 | 25,9 | 1736 | 55,9 | 47,7 | 1787 | 25,8 | m |
| 1686 | 57,5 | 20,7 | 1737 | 55,9 | 47,4 | 1788 | 19,9 | m |
| 1687 | 57,6 | 16,4 | 1738 | 55,8 | 46,9 | 1789 | 14,0 | m |
| 1688 | 57,6 | 12,4 | 1739 | 56,1 | 46,8 | 1790 | 8,1 | m |
| 1689 | 57,6 | 8,9 | 1740 | 56,1 | 45,8 | 1791 | 2,2 | m |
| 1690 | 57,5 | 8,0 | 1741 | 56,2 | 46,0 | 1792 | 0,0 | 0,0 |
| 1691 | 57,5 | 5,8 | 1742 | 56,3 | 45,9 | 1793 | 0,0 | 0,0 |
| 1692 | 57,3 | 5,8 | 1743 | 56,3 | 45,9 | 1794 | 0,0 | 0,0 |
| 1693 | 57,6 | 5,5 | 1744 | 56,2 | 44,6 | 1795 | 0,0 | 0,0 |
| 1694 | 57,3 | 4,5 | 1745 | 56,2 | 46,0 | 1796 | 0,0 | 0,0 |
| 1695 | 57,2 | 3,2 | 1746 | 56,4 | 46,2 | 1797 | 0,0 | 0,0 |
| 1696 | 57,2 | 3,1 | 1747 | 55,8 | m | 1798 | 0,0 | 0,0 |
| 1697 | 57,3 | 4,9 | 1748 | 55,5 | m | 1799 | 0,0 | 0,0 |
| 1698 | 57,3 | 4,2 | 1749 | 55,0 | m | 1800 | 0,0 | 0,0 |
| 1699 | 56,9 | 5,5 | 1750 | 54,1 | m | | | |
| 1700 | 57,1 | 5,1 | 1751 | 54,0 | m | | | |
| 1701 | 57,0 | 5,2 | 1752 | 53,3 | m | | | |
| 1702 | 56,9 | 5,5 | 1753 | 52,6 | m | | | |
| 1703 | 56,6 | 5,4 | 1754 | 51,8 | m | | | |
| 1704 | 57,1 | 6,1 | 1755 | 50,7 | m | | | |
| 1705 | 56,7 | 5,7 | 1756 | 49,9 | m | | | |
| 1706 | 56,8 | 5,8 | 1757 | 49,1 | m | | | |
| 1707 | 57,0 | 6,1 | 1758 | 47,7 | m | | | |
| 1708 | 56,7 | 5,9 | 1759 | 46,8 | m | | | |
| 1709 | 57,0 | 6,6 | 1760 | 45,7 | m | | | |
| 1710 | 56,9 | 6,4 | 1761 | 44,8 | m | | | |
| 1711 | 56,7 | 6,7 | 1762 | 43,9 | m | | | |
| 1712 | 56,9 | 6,9 | 1763 | 42,9 | m | | | |
| 1713 | 56,8 | 5,6 | 1764 | 41,5 | m | | | |
| 1714 | 56,6 | 5,1 | 1765 | 39,5 | m | | | |
| 1715 | 56,6 | 6,5 | 1766 | 36,7 | m | | | |
| 1716 | 56,5 | 10,0 | 1767 | 33,8 | m | | | |
| 1717 | 56,6 | 12,4 | 1768 | 31,0 | m | | | |
| 1718 | 56,5 | 14,5 | 1769 | 40,0 | 0,0 | | | |
| 1719 | 56,6 | 16,3 | 1770 | 49,1 | m | | | |
| 1720 | 56,3 | 18,1 | 1771 | 46,2 | m | | | |
| 1721 | 56,6 | 20,7 | 1772 | 43,1 | m | | | |
| 1722 | 56,1 | 22,6 | 1773 | 39,9 | m | | | |
| 1723 | 56,3 | 25,8 | 1774 | 36,6 | m | | | |
| 1724 | 56,4 | 27,7 | 1775 | 33,6 | m | | | |
| 1725 | 56,0 | 29,7 | 1776 | 30,5 | m | | | |
| 1726 | 56,1 | 32,6 | 1777 | 42,8 | 0,0 | | | |
| 1727 | 55,9 | 34,9 | 1778 | 55,2 | m | | | |
| 1728 | 55,9 | 36,4 | 1779 | 49,9 | m | | | |
| 1729 | 56,0 | 39,2 | 1780 | 44,0 | m | | | |
| 1730 | 55,9 | 41,4 | 1781 | 37,6 | m | | | |
| 1731 | 55,5 | 44,2 | 1782 | 47,2 | 0,0 | | | |
| 1732 | 55,9 | 46,4 | 1783 | 56,8 | m | | | |
| 1733 | 55,8 | 48,3 | 1784 | 47,5 | m | | | |
| 1734 | 55,6 | 49,1 | 1785 | 42,9 | m | | | |

m = motoring

**10.3 [Reference Fuels]**

## 10.4 Determination of System Equivalence

According to 5.3.1, other systems or analyzers (candidates) may be accepted if they yield equivalent results. The determination of system equivalency shall be based on a 7 sample pair (or larger) correlation study between the candidate system and one of the accepted reference systems of this standard using the appropriate test cycle. The equivalency criterion to be applied shall be the two-sided Student "t" test.

This statistical method examines the hypothesis that the population mean value for an emission measured with the candidate system does not differ from the population mean value for that emission measured with the candidate system. The hypothesis shall be tested on the basis of a 1 % significance level of the "$t$" value. The "$t$" values for 7 to 10 sample pairs are given in table 9. If the $t$ value calculated according to the formula 79 below is greater than the tabulated "$t$" value, the candidate system is not equivalent.

The following procedure shall be applied. The indices R and C refer to the reference and candidate system, respectively.

a)      At least 7 tests shall be conducted with the candidate and reference systems preferably operated in parallel. The number of tests is referred to as $n_R$ and $n_C$.

b)      The mean values $x_R$ and $x_C$ and the standard deviations $s_R$ and $s_C$ shall be calculated.

c)      The test value $t$ shall be calculated as follows:

$$t = \frac{x_C - x_R}{\sqrt{(n_C - 1) \times s_C^2 + (n_R - 1) \times s_R^2}} \times \sqrt{\frac{n_C \times n_R \times (n_C + n_R - 2)}{n_C + n_R}} \tag{79}$$

d)      The test value $t$ shall be compared to the tabulated "$t$" value corresponding to the respective number of tests indicated in table 9 below.  If larger sample sizes are selected, the degrees of freedom shall be calculated as $(n_C + n_R - 2)$ and the "$t$" value taken from statistical tables for 1 % significance (99 % confidence).

**Table 9        "$t$" values for selected sample sizes**

| Sample Size | Degrees of Freedom | "$t$" Value |
|:---:|:---:|:---:|
| 7 | 12 | 3,055 |
| 8 | 14 | 2,977 |
| 9 | 16 | 2,921 |
| 10 | 18 | 2,878 |

e)      The equivalency shall be determined, as follows:

-      if $t < $ "$t$", then candidate system is equivalent to reference system of this standard

-      if $t \geq $ "$t$", then candidate system is different from reference system of this standard

## 10.5   Carbon flow check

### 10.5.1          Introduction

All but a tiny part of the carbon in the exhaust comes from the fuel, and all but a minimal part of this is manifest in the exhaust gas as $CO_2$.  This is the basis for a system verification check based on $CO_2$ measurements.

The flow of carbon into the exhaust measurement systems is determined from the fuel flow rate. The flow of carbon at various sampling points in the emissions and particulate sampling systems is determined from the $CO_2$ concentrations and gas flow rates at those points.

In this sense, the engine provides a known source of carbon flow, and observing the same carbon flow in the exhaust pipe and at the outlet of the partial flow PM sampling system verifies leak integrity and flow measurement accuracy. This check has the advantage that the components are operating under actual engine test conditions of temperature and flow.

Figure 14 shows the sampling points at which the carbon flows shall be checked.  The specific equations for the carbon flows at each of the sample points are given below.
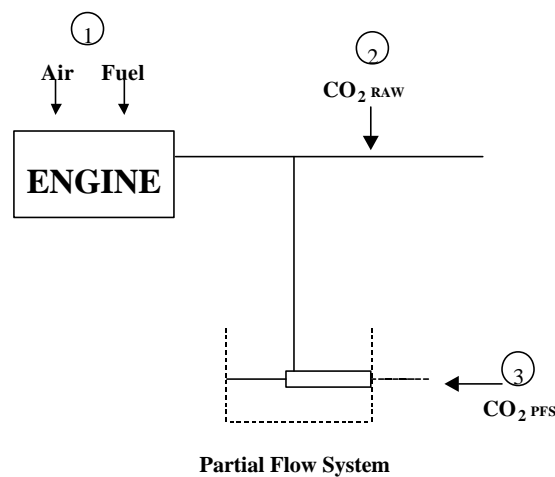


**Figure 14 — Measuring points for carbon flow check**

### 10.5.2          Carbon flow rate into the engine (location 1.)

The carbon mass flow rate into the engine for a fuel $C_bH_aO_e$ is given by:

$$q_{mCf} = \frac{12b}{12b + a + 16e} \cdot q_{mf} \tag{80}$$

where

$q_{mf}$          =          fuel mass flow rate, kg/s

### 10.5.3          Carbon flow rate in the raw exhaust (location 2.)

The carbon mass flow rate in the exhaust pipe of the engine shall be determined from the raw $CO_2$ concentration and the exhaust gas mass flow rate:

$$q_{mCe} = \left( \frac{c_{CO2,r} - c_{CO2,a}}{100} \right) \cdot q_{mew} \cdot \frac{12}{MW_{exhaust}} \tag{81}$$

where

$c_{CO2,r}$                    =          wet $CO_2$ concentration in the raw exhaust gas, %

| $c_{CO2,a}$ | = | wet $CO_2$ concentration in the ambient air, % (around 0,04 %) |
| $q_{mew}$ | = | exhaust gas mass flow rate on wet basis, kg/s |
| $MW_{exhaust}$ | = | molecular weight of exhaust gas |

If $CO_2$ is measured on a dry basis it shall be converted to a wet basis according to 8.1

## 10.5.4 Carbon flow rate in the partial flow dilution system (location 3.)

For the partial flow dilution system, the splitting ratio also needs to be taken into account. The carbon flow rate shall be determined from the dilute $CO_2$ concentration, the exhaust gas mass flow rate and the sample flow rate:

$$q_{mCp} = \left( \frac{c_{CO2,d} - c_{CO2,a}}{100} \right) \cdot q_{mdew} \cdot \frac{12}{MW_{exhaust}} \cdot \frac{q_{mew}}{q_{mp}} \tag{82}$$

where

| $c_{CO2,d}$ | = | wet $CO_2$ concentration in the dilute exhaust gas at the outlet of the dilution tunnel, % |
| $c_{CO2,a}$ | = | wet $CO_2$ concentration in the ambient air, % (around 0,04 %) |
| $q_{mew}$ | = | exhaust gas mass flow rate on wet basis, kg/s |
| $q_{mp}$ | = | sample flow of exhaust gas into partial flow dilution system, kg/s |
| $MW_{exhaust}$ | = | molecular weight of exhaust gas |

If $CO_2$ is measured on a dry basis, it shall be converted to wet basis according to 8.1

## 10.5.5 [Carbon flow rate in the full flow dilution system (location 3.)]

## 10.6   Example of Calculation Procedure

### 10.6.1   Basic data for stoichiometric calculations

| | | |
|---|---|---|
| Atomic weight of hydrogen | 1,00794 | |
| Atomic weight of carbon | 12,011 | |
| Atomic weight of sulfur | 32,065 | |
| Atomic weight of nitrogen | 14,0067 | |
| Atomic weight of oxygen | 15,9994 | |
| Atomic weight of argon | 39,9 | |
| Molar weight of water | 18,01534 | g/mol |
| Molar weight of  carbon dioxide | 44,01 | g/mol |
| Molar weight of  carbon monoxide | 28,011 | g/mol |
| Molar weight of oxygen | 31,9988 | g/mol |
| Molar weight of nitrogen | 28,011 | g/mol |
| Molar weight of nitric oxide | 30,008 | g/mol |
| Molar weight of nitrogen dioxide | 46,01 | g/mol |
| Molar weight of sulfur dioxide | 64,066 | g/mol |
| Molar volume of water | 22,401 | l/mol |
| Molar volume of carbon dioxide | 22,262 | l/mol |
| Molar volume of oxygen | 22,392 | l/mol |
| Molar volume of nitrogen | 22,390 | l/mol |
| Molar volume of nitric oxide | 22,391 | l/mol |
| Molar volume of nitrogen dioxide | 21,809 | l/mol |
| Molar volume of sulfur dioxide | 21,891 | l/mol |
| Molar volume of  argon | 22,4 | l/mol |

### 10.6.2          Gaseous Emissions (Diesel Fuel)

The measurement data of an individual point of the test cycle (data sampling rate of 1 Hz) for the calculation of the instantaneous mass emission are shown below. In this example, CO and $NO_x$ are measured on a dry basis, HC on a wet basis. The HC concentration is given in propane equivalent (C3) and has to be multiplied by 3 to result in the C1 equivalent. The calculation procedure is identical for the other points of the cycle.

| $T_{a,i}$ (K) | $H_{a,i}$ (g/kg) | $W_{act}$ kWh | $q_{mew,i}$ (kg/s) | $q_{maw,i}$ (kg/s) | $q_{mf,i}$ (kg/s) | $c_{HC,i}$ (ppm) | $c_{CO,i}$ (ppm) | $c_{NOx,i}$ (ppm) |
|---|---|---|---|---|---|---|---|---|
| 295 | 8,0 | 40 | 0,155 | 0,150 | 0,005 | 10 | 40 | 500 |

The following fuel composition is considered:

| Component | Molar ratio | % Mass |
|-----------|-------------|--------|
| H | $a$ = 1,8529 | $w_{ALF}$ = 13,45 |
| C | $b$ = 1,0000 | $w_{BET}$ = 86,50 |
| S | $g$ = 0,0002 | $w_{GAM}$ = 0,050 |
| N | $d$ = 0,0000 | $w_{DEL}$ = 0,000 |
| O | $e$ = 0,0000 | $w_{EPS}$ = 0,000 |

**Step 1: Dry/wet correction (8.1):**

Formula (14): $\quad k_f \quad = \quad$ 0,055584 x 13,45 - 0,0001083 x 86,5 - 0,0001562 x 0,05 = 0,7382

Formula (8): $\quad k_W \quad = \left(1 - \dfrac{1,2434 \times 8 + 111,12 \times 13,45 \times \dfrac{0,005}{0,148}}{773,4 + 1,2434 \times 8 + \dfrac{0,005}{0,148} \times 0,7382 \times 1000}\right) \times 1,0085 \quad = 0,9331$

Formula (7): $\quad\quad c_{CO,i}$ (wet) $\quad\quad = \quad$ 40 x 0,9331 = 37,3 ppm

$\quad c_{NOx,i}$ (wet) $\quad = \quad$ 500 x 0,9331 = 466,6 ppm

**Step 2: NO$_x$ correction for temperature and humidity (8.2):**

Formula (15): $\quad k_{h,D} = \dfrac{1}{1 - 0,0182 \times (8,00 - 10,71) + 0,0045 \times (295 - 298)} = 0,9654$

**Step 3: Calculation of the instantaneous mass emission using u values from table 4 (8.3.2.4):**

Formula (22): $\quad m_{HC,i} \quad = \quad$ 0,000478 x 10 x 3 x 0,155 $\quad\quad\quad = \quad$ 0,00222 g/s

$\quad\quad\quad m_{CO,i} \quad = \quad$ 0,000966 x 37,3 x 0,155 $\quad\quad\quad = \quad$ 0,00558 g/s

$\quad\quad\quad m_{Nox,i} \quad = \quad$ 0,001587 x 466,6 x 0,9654 x 0,155 $\quad = \quad$ 0,1108 g/s

**Step 4: Integration of the instantaneous mass emission over the cycle (8.3.2.4):**

The following calculation is assumed for the WHTC cycle (1800 s) and the same emission in each point of the cycle.

Formula (22): $\quad m_{HC} \quad\quad = \quad \displaystyle\sum_{i=1}^{1800} 0,00222 \quad = \quad$ 3,96 g/test

$\quad\quad\quad m_{CO} \quad\quad = \quad \displaystyle\sum_{i=1}^{1800} 0,00558 \quad = \quad$ 10,04 g/test

$\quad\quad\quad m_{NOx} \quad\quad = \quad \displaystyle\sum_{i=1}^{1800} 0,1108 \quad = \quad$ 199,44 g/test

**Step 5: Calculation of the specific emissions (8.3.2.6):**

Formula (26): $\quad\quad\quad HC \quad = \quad$ 3,96 / 40 $\quad\quad\quad\quad$ = 0,10 g/kWh

$\quad\quad\quad CO \quad = \quad$ 10,04 / 40 $\quad\quad = \quad$ 0,25 g/kWh

$\quad\quad\quad NO_x \quad = \quad$ 199,44 / 40 $\quad = \quad$ 4,99 g/kWh

### 10.6.3 Particulate Emission (Diesel Fuel)

Particulate measurement is based on the principle of sampling the particulates over the complete cycle, but determining the sample and flow rates ($M_{SAM}$ and $G_{EDF}$) during the individual points of the cycle. The calculation of $G_{EDFW}$ depends on the system used. In the following example, a system with flow measurement according to 8.3.3.5, method a) is used.

The following measurement data are assumed in this example:

| $W_{act}$ | $q_{mew,i}$ | $q_{mf,i}$ | $q_{mdw,i}$ | $q_{mdew,i}$ | $m_f$ | $m_{se}$ |
|---|---|---|---|---|---|---|
| kWh | (kg/s) | (kg/s) | (kg/s) | (kg/s) | (mg) | (kg) |
| 40 | 0,155 | 0,005 | 0,0015 | 0,0020 | 1,700 | 1,515 |

### Step 1: Calculation of $m_{edf}$ (clause 8.3.3.5):

Formula (31):  $r_{dil,i}$  $= \dfrac{0,002}{(0,002 - 0,0015)}$   $=$   4

Formula (30):  $q_{medf,i}$   $= 0,155 \times 4$   $=$   0,62 kg/s

Formula (29):  $m_{edf}$   $= \displaystyle\sum_{i=1}^{1800} 0,62$   $=$   1116 kg/test

### Step 2: Calculation of the particulate mass emission (clause 8.3.3.5):

Formula (28):  $m_{PM}$  $=$   $\dfrac{1,7}{1,515} \times \dfrac{1116}{1000}$   $=$   1,252 g/test

### Step 3: Calculation of the specific emissions (8.3.3.6):

Formula (34):  $PM$  $=$  1,252 / 40   $= 0,031$ g/kWh