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Consistent requirements specified for novel measuring instruments (prototypes) and comparison with European legislative requirements

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Content

1. SCOPE

Concerns related to the adverse health effects of automotive exhaust aerosols have driven the regulatory authorities worldwide to adopting measures for the control of the particulate matter (PM) emissions of new registered diesel vehicles and to verify the emission performance over the useful life of the vehicle. The particulate emission performance at a certification stage was traditionally monitored gravimetrically by means of collecting samples from a Constant Volume Sampler (CVS). For the periodic inspection of the emission performance, however, a simpler approach is employed that monitors the opacity of the exhaust gas under free accelerations.

European legislation has introduced continuously tighter emission standards, and by 2005 (Euro 4 / Euro IV stage) the limit values were almost one order of magnitude lower than those introduced in the first stage in 1992. However, the Clean Air For Europe (CAFÉ) study [[i]] concluded in 2005 that "*significant negative impacts will persist even with effective implementation of current legislation*". The projected PM levels in Europe were estimated to result in "*a 5.5 months loss in statistical life, or equivalently in 272,000 premature deaths*". In response, the European Commission requested a further tightening of the PM emission standards at a level that would necessitate the mandatory installation of the best technology Diesel Particulate Filters (DPFs) in all compression ignition passenger cars [[ii]]. Recognizing that the gravimetric procedure would not be sensitive enough to discriminate between the very efficient wall flow Diesel Particulate Filters (DPFs) and flow-through particulate filters, a particle number limit was also introduced which became effective at a Euro 5b stage (9/2011 – [[iii]]) for passenger cars. A particle number limit will also be introduced for the certification of Euro VI technology Heavy Duty Engines [[iv]].

The periodic inspection and maintenance procedures, however, have not been amended to reflect the recent advances in diesel aftertreatment technology (widespread use of DPFs) and the shift of the certification procedures to particle number limit. The current opacimeters are not sensitive enough to quantify the emission performance of DPF-equipped diesels and there are concerns whether they will be able to identify malfunctions (e.g. cracks) of the DPF. In order to adapt the exhaust emission control to technical progress, the establishment of novel measuring instruments for the periodic emission control will become necessary in the near future.

Significant progress has already been made in aerosol instrumentation, and some instruments allowing direct sampling from the exhaust and, at the same time, being much more sensitive in detecting particles compared to opacimeters that have appeared on the market. A European project under the acronym TEDDIE (TEst (D) DIEsel) [[v]], coordinated by the International Motor Vehicle Inspection Committee (CITA), is currently investigating the performance of several candidate instruments. The objective of the TEDDIE project is to define new test procedures and equipment for measuring emissions of nitric oxide (NO), nitrogen dioxide (NO_2), and particulate matter (PM) from diesel vehicles during periodic technical inspection (PTI). The investigated parameters for the PM measurement were the accuracy and stability within tests with reference engines under constant load and speed, as well as practicability, the dynamic reproducibility, and the accuracy under free acceleration using an opacimeter AVL 439 as a reference. The results of the study are expected to be published by the end of 2011.

In addition, two relevant projects were realized in Germany: The Project Emission 2010 (start in 2006 by DEKRA, TÜV, ASA, ZDK) resulted in the following conclusions:

- the OBD does not cover all emission aspects
- the reference values used during periodic emission control are too high and
- the new instruments working on scattered light are much more sensitive and precise [[vi]].

Furthermore, the German Garage Equipment Organisation (ASA) launched in 2010 -together with PTB- the project "Partikeldiagnostik" with the aim to build up know-how on particle diagnostic for periodic inspection with new measuring principles (e.g. scattered light).

Significant progress was also made in Switzerland where an alternative procedure for the inspection of the DPF performance installed in construction machinery [[vii]] is based upon particle number counting. During low and high idle constant speed, the number concentration is measured within several minutes with handheld instruments. The swiss legislation with detailed requirements is planned to be introduced by April 2012.

The various candidate instruments envisaged in the aforementioned studies operate on different principles (diffusion charging and number counting, light scattering, photoacoustic spectroscopy) and, therefore, measure a different aerosol properties. Thus implementation of these prototypes in legal metrology requires a well-based metrological validation.

This project will develop a metrological background for the validation of novel instruments measuring the concentration of combustion particles in exhaust gases from diesel vehicles, which can be used for the regulatory periodic emission control of vehicles. The capability of these instruments shall be investigated with regard to the regulated requirements.

The purpose of this report is to collate and review the technical requirements laid down in the European regulation but, also through national regulatory authorities for the calibration of opacimeters, in order to establish a frame of reference for the establishment of the calibration procedures for the novel instrumentation.

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2. European regulations

The first Directive addressing roadworthiness checks in Europe was introduced in 1977 [[viii]]. The requirements laid down applied to buses, coaches, heavy goods vehicles, trailers and semi-trailers over 3.5 tonnes, taxis and ambulances, but did not address their emission performance. The Directive was subsequently amended in 1988 [[ix]] to include light goods vehicles in the roadworthiness procedure. Two subsequent Directives in 1991 introduced comitology procedures [[x]] and extended roadworthiness testing to private cars [[xi]].

The first Directive for the introduction of exhaust gas emission testing in regular periodic inspection checks came into force in 1992 [[xii]]. The intention of this Directive was to ensure that the emissions remain at a low level throughout the useful life of the vehicle, and to harmonize the test procedures already applicable in most member states. Recognizing that application of the type-approval procedures for testing gaseous emissions and fumes emitted by all types of vehicles presents some difficulty, it was decided to employ alternative, simpler, quicker and less expensive procedures for roadworthiness checks. At that point, it was conceived that measurement of the opacity of the diesel exhaust fumes was an adequate indicator of the condition of the vehicle's state of maintenance, with regard to emission. It was stated though that "*this Directive will be adapted from time to time to take into account developments in vehicle construction which facilitate in-service testing and in test methods which reflect more closely the actual conditions in which a vehicle is used*".

The Directive specified, that the measurement of the exhaust gas opacity shall be performed in free acceleration tests (where the engine is accelerated against its own inertia) as described in Directive 72/306/EEC [xiii]. At least six successive free accelerations shall be performed until the maximum opacity values of four consecutive readings are situated within a band width of 0·25 m^{-1} and do not form a decreasing sequence. The absorption coefficient to be recorded shall be the arithmetic mean of these four values.

The recorded absorption coefficient should not exceed the level recorded on the manufacturers plate of the vehicle. In cases where this information was not available or where Member States' competent authorities decided not to use these plate values as a reference, the measured absorption coefficients had to be lower than 2.5 m^{-1} for aspired diesel engines and less than 3.0 m^{-1} for turbo-charged diesel engines.

There were also some provisions for the use of alternative instrumentation. In this case equivalent limit values should be applied. With respect to the opacimeter specifications the Directive referred to Directive 72/306/EEC [xiii]. This particular document includes requirements for the construction of the opacimeters (smoke chamber, light source, receiver, measuring scales, response time), its calibration (zeroing, use of a calibrated screen, determination of the effective path length), but also specifications for exhaust sampling (monitoring and control of temperature and pressure operating ranges, isokinetic sampling, etc.).

Directive 96/96/EC [xiv] consolidated all amendments of the original Directive [viii] into a single document.

Directive 1999/52/EC [xv] established a technical adaptation which better described the testing procedure of roadworthiness testing of diesel-engined vehicle emissions, recognizing at the same time that further work needs to be done in the field of developing alternative test procedures to check the maintenance conditions of diesel-engined vehicles, particularly concerning particulates and nitrogen oxides. More specifically, the Directive introduced provisions for engine preconditioning prior to the test, to ensure that the engine is fully warm. The document also introduced instructions for leakage inspection, turbocharger conditioning, and testing of vehicles with automatic transmissions. The emission limits remained the same, but the failure conditions were redefined through the use of the arithmetic mean of the last three free acceleration cycles, neglecting statistical outliers.

Directive 2003/27/EC [xvi] introduced a lower absorption coefficient limit of 1.5 m^{-1}, applicable to Euro 4/IV and latest technology light-duty and heavy-duty diesel vehicles. This amendment was based on the findings of working group experts from the International Motor Vehicle Inspection Committee (CITA) and other relevant organisations which were established by the Commission in 2000. The group concluded that the applicable soot emission limits at that time were invariably well above what the vehicle is capable of achieving in practice, provided that it is properly maintained: the current limits are therefore not as effective as they could be in facilitating the detection of gross emitters, i.e. vehicles whose exhaust emissions are at least 50% more than it would be expected from a properly maintained vehicle.

A consolidated version of the Directive including all aforementioned amendments was published in 2009 [xvii]. The document once again stated that "*The Commission shall adopt the separate Directives necessary to define the minimum standards and <u>methods for testing</u> the items listed in Annex II, as well as <u>any amendments necessary to adapt those standards and methods to technical progress</u>.*", "*assisted by a committee on the adaptation to technical progress of the Directive on roadworthiness tests for motor vehicles and their trailers.*"

The European Commission following the recommendations of the aforementioned committee, came up with a new Directive in 2010 [xviii] which, however, did not bring any modifications in the emission testing procedures or limits. The new Directive mainly focused on the inclusion of modern electronic systems in the list of items to be tested. The Directive clearly stated though that "*Further work needs to be done in the field of developing alternative test procedures to check the maintenance condition of diesel driven vehicles, particularly concerning NOx and particulates, <u>taking into account new emission after-treatment systems</u>.*" It should be emphasized that, for the first time, the Directive refers to new emissions after-treatment systems which include Diesel Particulate Filters (DPFs).

2.1. Opacimeter operating principle

Opacimeters are devices used to measure the opacity (N) of the exhaust. The measuring principle is described in the ISO standard: ISO 11614 [xix]. Their operating principle is based on the measurement of the fraction of light transmitted through a well-defined smoke-obscured path (measuring zone) that eventually reaches a receiver (e.g. a photoelectric device), referred to as transmittance (τ):

$$\tau = \frac{\Phi}{\Phi_0} \times 100 = 100 - N \qquad , \qquad \text{eq. 1}$$

where Φ is the light intensity at the receiver when the measuring zone is filled with exhaust gas, and Φ_0 is the light intensity at the receiver when the measuring zone is filled with clean air.

According to the Beer-Lambert law, the transmittance can be related to the light extinction coefficient[1] (k) through:

$$k = -\frac{1}{L} \times \ln\left(\frac{\tau}{100}\right) = -\frac{1}{L} \times \ln\left(1 - \frac{N}{100}\right) \qquad , \qquad \text{eq. 2}$$

where L is the effective length of the smoke-obscured path (through which the light is transmitted).

[1] While light extinction is due to both absorption and scattering of light from the particles occupying the measuring zone, the "light extinction coefficient" is customarily referred to as "light absorption coefficient". In the present document the two terms are used interchangeably and refer to the same property.

2.2. CALIBRATION REQUIREMENTS LAID DOWN IN EUROPEAN LEGISLATION

In addition to roadworthiness test procedures [xiii], opacimeters have also been employed since 1999 for the certification of heavy duty diesel engines [iv]. The latter requires real time measurements of the opacity (at a frequency of at least 20 Hz) over the European Load Response (ELR) cycle, which is comprised of a sequence of engine load and engine speed step changes. Opacity limits for heavy duty diesel engines will be phased out at a Euro VI stage, owing to the introduction of the more sensitive particle number measurement procedure [xx]. This section summarizes the opacimeter calibration requirements laid down in the two regulations [xiii, iv].

ROADWORTHINESS LEGISLATION (DIRECTIVE 72/306/EEC):

DETERMINATION OF THE EFFECTIVE LENGTH

Directive 72/306/EEC [xiii] describes a method to determine the effective path length of opacimeters for the case that the gas filling the measuring zone is not of constant opacity (e.g. due to scavenging air used to protect the light source and the photoelectric cell). The calibration procedure is based on successive measurements with the opacimeter operating normally and the opacimeter being modified, so that the test gas fills a well-defined length L_0 that should be close to the presumed effective length of the opacimeter. The regulation allows the use of either exhaust gas of constant opacity or a light-absorptive gas of a gravimetric density similar to that of the exhaust gas. Furthermore, it requires the use of at least four gases showing opacity readings evenly spaced between the 20 % and 80 % range. By comparing the reading N of the opacimeter operating normally with the reading N_0 of the opacimeter modified so that the test gas fills a well-defined length L_0, it is possible to derive an effective length for each of the four gases:

$$L = L_0 \frac{T}{T_0} \frac{\log\left(1 - \frac{N}{100}\right)}{\log\left(1 - \frac{N_0}{100}\right)} \quad , \qquad \text{eq. 3}$$

where T and T_0 are the mean gas temperatures in K at the two configurations. The effective length is then determined as the arithmetic mean of the four calculated values.

The Directive also allows the determination of the effective length through correlation with another type of opacimeter for which the effective length is known. However, it does not specify how these correlation tests should be performed.

VALIDATION CHECKS

Directive 72/306/EEC [xiii] also describes a check to verify the performance of the measurement apparatus without, however, clarifying the necessary measurement frequency. This check shall be performed using a screen representing a gas having a light extinction coefficient between 1.6 and 1.8 m^{-1}, ±0.025 m^{-1}. The opacimeter indication shall not differ from this value by more than 0.05 m^{-1}.

ADJUSTMENT OF THE OPACIMETER

Directive 72/306/EEC [xiii] also describes a procedure for adjusting the zero levels and checking the full scale indication. More specifically, the directive requires that the electric circuit of the photoelectric cell and of the indicating dial is adjustable so that the pointer can be reset at zero, when the light flux passes through the smoke chamber filled with clean air or through a chamber having identical characteristics. It also requires, that when the lamp switched off and the electric measuring circuit is open or short-circuited, the reading on the absorption coefficient scale is ∞, and it remains at ∞ with the measuring circuit reconnected.

HEAVY DIESEL DUTY ENGINE REGULATION CERTIFICATION REGULATION (R49):

DETERMINATION OF THE EFFECTIVE LENGTH

Regulation R49 [iv] refers to the procedures laid down in ISO standard 11614 [xix] for the determination of the effective length. As with Directive 72/306/EEC [xiii], the ISO standard envisages either the use of an opacimeter, for which the effective length is known, or checks against the same opacimeter modified in a way so that the exhaust fills a known length.

With respect to the second approach (tests with and without modification of the opacimeter operation), the procedures are broadly similar to those described in Directive 72/306/EEC [xiii], but the ISO standard requires tighter control of all operating parameters. In particular, the standard requires that:

- The tests are performed at the lowest limit of temperature and sample flow (i.e. lowest sample pressure and highest scavenge air pressure) specified by the manufacturer.
- The signal of the photoelectric cell shall be connected to a recorder with a response time of less than 1 s, and a sensitivity such that 4 mm correspond to not more than 0.05 m^{-1} for smoke of opacity 1.7 m^{-1}.
- Exhaust gas samples are passed through a damping chamber with a well-defined minimum volume (at least 20 times the flow through the sample line in 1 s) to ensure satisfactory constancy of opacity.
- Provisions are required to ensure that any modifications made (including the use of the damping chamber) will not change the true mean gas temperature over the effective length or the light source performance.
- At least 10 readings (each reading comprising a comparison of modified and unmodified conditions) shall be taken with exhaust gas densities corresponding to levels of between 1 m^{-1} and 2 m^{-1}. Provisions are also made to allow sufficient time for the instrument to stabilize following each modification (10 s or the response time of the mean temperature indicator, whichever is longer) and to check the zero levels with clean air at the end of each single measurement. Additional tests shall be performed if the average effective length (calculated according to eq. 3) is not statistically valid to an accuracy of ± 1% with 95% confidence [xxi].

The ISO standard also describes a procedure for the determination of the effective length of the opacimeter under calibration against an opacimeter with a known effective length. The two opacimeters need to simultaneously sample exhaust operating at the minimum sample flowrate and within the lower temperature limits. The ISO standard requires that at least 10 readings are taken using smoke between 40% and 60% opacity and the effective length be calculated for each measurement in accordance with eq. 3 (where subscript 0 corresponds to the operating parameters of the opacimeter of known effective length). The calculated numerical average of the ten effective length values is considered to be the effective length of the opacimeter under calibration unless this result is not statistically valid to an accuracy of

±1% with 95% confidence (accounting for the known accuracy of the reference instrument) in this case additional tests are performed until this statistical requirement is satisfied.

Regulation R49 adds the additional constraint of a minimum exhaust gas velocity of 20 m/s for the calibration of the optical path length of full flow opacimeters (designed to measure the opacity of the full exhaust plume).

VALIDATION CHECKS

Regulation R49 [iv] also requires some periodic in-use checks to be performed in line with the ISO 11614 standard. These include:

1. Calibration of the pressure transducer and thermocouple (measuring the pressure and temperature inside the measuring zone, respectively) every 6 months.
2. Calibration of the opacimeter at least every 7.5 days against a mesh or neutral optical density filter, representing a gas opacity between 15% and 80% of full scale and known to an accuracy of ±1 % opacity. The opacimeter indication shall be within 2% opacity of the known value of the filter, if the intermediate check screen employed does not have an opacity equivalent to an extinction coefficient of between 1.5 m^{-1} and 2 m^{-1}, calculated with the effective optical path length.

Regulation R49 [iv] also introduces an extra linearity requirement on a three-month basis (or whenever a system repair or change is made, that could influence calibration) employing neutral density filters having nominal opacities of approximately 10%, 20% and 40%. The opacimeter indications have to agree within ± 2 % opacity of the nominal value of the neutral density filters.

ADJUSTMENT OF THE OPACIMETER

Regulation R49 [iv] includes requirements for an adjustment of both zero and full scale levels in opacity readout mode. In particular, the regulation requires that with no blockage of the opacimeter light beam, the readout shall be adjusted to 0.0 % ± 1.0 % opacity, whereas when the light is prevented from reaching the receiver, the readout shall be adjusted to 100.0 % ± 1.0 % opacity.

2.3. OPACIMETER SPECIFICATIONS

Table 1 summarizes the opacimeter specifications laid down in European regulations.

3. SUMMARY OF THE ACTUAL NATIONAL REQUIREMENTS FOR MEASURING SOOT EMISSIONS OF PARTICIPATING COUNTRIES

The requirements for the opacimeter are not included in the European Measuring Instruments Directive (MID). Therefore it was necessary to consider the various national requirements for instruments measuring the concentration of combustion particles in exhaust gases from diesel vehicles within the periodic emissions control.

The study scrutinized the requirements laid down in the national regulations of the participating countries (CH, FIN, GER), but also reviewed those of other European member states to ensure that no special features were missed.

Table 1: Opacimeter specifications laid down in the European regulation.

	Directive 72/306/EEC	R49
Application	Free acceleration test	ELR test cycle
Measured quantity	Opacity (0%-100%) Light extinction coefficient (0 m^{-1}- ∞ m^{-1})	Opacity (0%-100%) Light extinction coefficient (0 m^{-1}- ∞ m^{-1})
Stray light interference	<1% for exhaust having a light extinction coefficient of 1.7 m^{-1}.	
Accuracy	0.025 m^{-1} when measuring exhaust having a light extinction coefficient of 1.7 m^{-1}.	Linearity of ±2% opacity.
Readability		0.1% opacity 0.01 m^{-1} light extinction coefficient
Electrical response time	Time necessary for the indicating dial to reach 90 percent of full scale deflection on insertion of a screen fully obscuring the photoelectric cell: 0.9-1.1 s.	The difference between the times when the opacimeter output reaches 10 and 90 percent of the full scale when the light source is interrupted or completely extinguished in less than 0.01 s: ≤0.05 s.
Physical response time	Time between the entry of the gas into the measuring apparatus and the complete filling of the smoke chamber: ≤0.4 s	The difference between the times when the output of a rapid response receiver reaches 10 and 90 per cent of the full deviation when the opacity of the gas being measured is changed in less than 0.1 s: ≤0.2 s
Filtering of the opacimeter responses	The damping of the electric measuring circuit shall be such that the initial overswing beyond the final steady reading after any momentary variation in input (e.g. the introduction of a calibration screen) does not exceed 4 percent of that reading in linear scale units.	A Bessel filter (a low pass second order filter) shall be applied to compute the 1 s average values from the instantaneous smoke readings.
Pressure in the measuring zone	The pressure of the exhaust gas in the smoke chamber shall not differ by more than 75 mm H_2O gauge (0.735 kPa gauge) from the atmospheric pressure.	The pressure of the gas in the measuring chamber shall not differ from the atmospheric pressure by more than 0.75 kPa. Where this is not possible by design, the opacimeter reading shall be converted into atmospheric pressure.
Temperature in the measuring zone	In order to avoid condensates forming in the measuring zone, the gas temperature at every point in the smoke chamber at the instant of measurement shall be between 70°C and a maximum temperature, specified by the opacimeter manufacturer.	The wall temperature of the measuring chamber shall be set to within ±5 K between 343 K (70 °C) and 373 K (100 °C), but in any case sufficiently above the dew point of the exhaust gas to prevent condensation. The measuring chamber shall be equipped with appropriate devices for measuring the temperature.
Pressure effect on opacimeter indications	The variations in the pressure of the gas to be measured and of the scavenging air (air flowing through the light source and the receiver of some opacimeters to protect them from fouling) shall not cause the extinction coefficient to vary by more than 0.05 m^{-1} in the case of a gas having an extinction coefficient of 1.7 m^{-1}.	The pressure variation of the gas and the scavenging air in the smoke chamber shall not cause the light extinction coefficient to vary by more than 0.05 m-1 in the case of a gas having an absorption coefficient of approximately 1.7 m-1 (or in the case of opacimeters having a full-scale reading of less than 2 m^{-1}, by more than 2% of the full scale).
Temperature effect on opacimeter indications	The readings over the allowed temperature range (70°C - manufacturer peak) should not vary by more than 0.1 m^{-1} if the chamber is filled with a gas having an extinction coefficient of 1.7 $m^{-1.}$	

Table 2: Results of the enquiry of the national requirements for opacimeters in some European member states

Country	**Title**
GER	PTB-A 18.9 Measuring instruments for road traffic - Opacimeters for engines with compression ignition as partial-flow opacity measuring instrument
CH	Verordnung des EJPD über Abgasmessgeräte für Verbrennungsmotoren (VAMV) vom 19. März 2006 (Stand am 2. Mai 2006)
	VAMV E Annexe 4: Specific requirements for measuring instruments for nanoparticles from combustion engines
	VAMV Annexe 2: Requirements for opacimeters following ISO11614 and EEC 72/306
	Erläuterungen zur Einreichung von Dieselrauchmessgeräten zur Bauartprüfung
	Eichformular für Dieselrauchmessgeräte
BIH	German approval accepted
MK	ISO11614, EEC 72/306
HR	ISO11614
SL	EEC 72/306
RO	German approval accepted
FR	NFR 10-025-1, NFR 10-025-2, NFR 10-025-3, NFR 10-025-4 (Annexe)
FI	Finland follows the EU directives concerning emission testing during vehicle inspection. Therefore there are no specific technical requirements for the opacimeters in use. The periodic vehicle inspection does not concern construction machines. Furthermore, in Finland the maximum value for the absorption coefficient is used and not the value recorded on the manufacturers' plate, except for cars where the value is higher. The Finnish Transport Safety Agency (Trafi) only provides instructions on how to perform emission testing and what results should be presented in the certificate.
BIH	German approval accepted
MK	ISO11614, EEC 72/306
HR	ISO11614
SL	EEC 72/306
RO	German approval accepted
FR	NFR 10-025-1, NFR 10-025-2, NFR 10-025-3, NFR 10-025-4 (Annexe)
GR	Official Government Gazette No 360 B, Harmonization with Directive 2003/27/EC (1.5 m-1 for Euro 4 and latest technology vehicles)
ES	Ensayos de verificacion de opacimetros
NL	Voorschriften meetmiddelen 1997
SERB	PRAVILNIK, O METROLOŠKIM USLOVIMA ZA OPACIMETRE, ("Sl. list SCG", br. 20/2003)
BG	ORDINANCE ON Measuring Instruments Subject to Metrological Control, Adopted by a Government Decree No. 239 from 24.10.2003, published in State Gazette 98/7.11.2003.
BLR	ISO 11614
PE	ISO 11614
UK	Specification for diesel smoke meters, including MOT/08/19/01, issued 10/2001, 3rd revision 1/2007
A	40. Novelle zu KDV 1967,§28a, EWG 77/143 in der Fassung EWG 92/55

The only national requirements for the opacimeters of the following countries are available in English or German translation: Switzerland [xxii], Germany [xxiii], France [xxiv], UK [xxv], Bulgaria [xxvi]. Of notable importance is that in Switzerland in the near future, with *VAMV Annex 4: Specific requirements for measuring instruments for nanoparticles from combustion engines* [xxvii], the measurement of the particle number concentration in exhaust gases is to be implemented for the first time in Europe in national legal metrology. Other national requirements are only available in the national language; some countries follow Directive 72/306 EEC [xiii] and other countries work according to ISO 11614 [xix]. The results of the enquiry are shown in Table 2.

3.1. Requirements for Opacimeters

The national requirements are substantially based on Directive 71/306 EEC [xiii] and ISO 11614 [xix]. In addition to the technical and metrological requirements, also the disturbances like electromagnetic compatibility [xxviii] and mechanical shock [xxix] as well as the requirements for the software [xxx] are considered. The technical requirements include the adjusting possibilities and controlling facilities, special equipment features, facilities for operation, control and display, protection and exchange of software components subject to mandatory verification. Furthermore, the requirements for markings and instructions for use, as well as the verification tests are defined.

The individual national requirements differ in some details regarding type testing, but these details do not influence the determination of uniform requirements for the evaluation of the novel instruments.

The justification procedure for the opacimeters is the same according to Directive 72/306 EEC [xiii] (see Chapter 2.2) and ISO 11614 [xix]. The opacimeters have to be calibrated with optical density filters and the correlation with the reference opacimeter has to be carried out on a range of test vehicles.

The differences are, on the one hand, in the design of the reference opacimeters which are not compared between the European member states and, on the other hand, in the diverse selection of the test vehicles. Furthermore, the operating modes differ between the free acceleration mode, on the one hand, and the continuous mode. The outcome is that the national justification procedures provide slightly different results for the reference opacimeters.

3.2. Requirements for other Measuring Instruments

Currently, the only regulatory requirements for the type testing of instruments other than opacimeters measuring diesel exhaust soot are the *Specific requirements for measuring instruments for nanoparticles from combustion engines* [xxii] which are to be implemented in the Swiss regulation in 2012. It should be stressed here that the particular regulation concerns construction machinery so the engine test procedure differs from that of diesel vehicles (the most important difference being the use of steady state testing rather than free acceleration tests). The whole procedure is designed around the possibility of checking for damage to the DPF that would result in some particles escaping the DPF.

Nanoparticles are there defined as “s*olid, mostly carbonic components in the exhaust gas from combustion engines. The particles have a mobility diameter in the range from about 20 nm to 300 nm. The condensing portions are not taken into account”.*

The measurand is the mobility diameter of the nanoparticles defined as “*a diameter of a spherical particle which exhibits the same electrical mobility as the measured particles when measured in a mobility analyser in accordance with ISO 15900-2009”* [xxxi]. The *measuring range for the particle number concentration of nanoparticles* is defined as “*at least from* $5x10^4$ cm^{-3} *to* $5x10^6$ cm^{-3}*”*. In addition to the nominal operating conditions, the error limits, permissible effect of disturbance influences, the measurement stability, the official measurement and other requirements are specified. The latter are:

- *“the step response of the measured value from 10 % to 90 % for a rectangular change in the input concentration (for increasing and decreasing concentration) shall last 4.5 s to 5.5 s (response time)*
- *the duration of the exhaust gas inflow during the sampling up to the display of the number concentration shall be less than 10 s (delay interval),*

the efficiency E of the measuring instrument designates the quotient of the displayed particle number concentration and the particle number concentration entering into the measuring instrument. The required limits of efficiency are*: E < 50 % (23 nm particles), 50 % < E (41 nm particles), 70 % < E (80 nm particles) < 130 %, E (200 nm particles) < 200 % and E < 5 % (30 nm droplets of tetracontane (number concentration up to* 10^5 cm^{-3}*))”.*

4. CANDIDATE INSTRUMENTATION

In order to identify candidate instrumentation to be tested within the framework of the ENV02 project, a call for interest will be launched in January 2012. A preliminary list of candidate instrumentation to be evaluated in the programme was already identified by the partners in a project meeting in November 2011 and includes:

- AVL Micro Soot Sensor: a photoacoustic soot sensor,
- Pegasor Particle Sensor: a type of diffusion charger that incorporates an ejector diluter for sampling,
- FH Nordwestschweiz (FHNW), MiniDiSC: a type of diffusion charger calibrated to provide both particle number and size distribution information.. (Attention should be paid to the fact that this instrument is not designed for emission measurements but as a personal monitor. Perhaps the manufacturer (FHNW or MatterAerosol/Testo) can provide a prototype for emission testing.)
- MAHA Machinenbau GmbH, MPM-4 or a newer version of this instrument: a portable sensor using light scattering.

Some of these instruments are capable of measuring directly at the exhaust, whereas others require some kind of conditioning (e.g. dilution and/or thermal treatment to remove interferences by volatile components and avoid condensation, or pressure fluctuation reduction). However, such conditioning of the exhaust may affect the accuracy, sensitivity and dynamic response of the measurements. In that respect, the candidate instrumentation to be assessed must include the conditioning devices necessary to sample directly from the vehicle tailpipe.

5. CALIBRATION REQUIREMENTS FOR THE NOVEL INSTRUMENTATION

The enquiry of the national requirements suggested that the Directive 72/306 EEC [[xiii]] be implemented in the respective national requirements of measuring instruments for road traffic in the European member states.

The opacimeter calibration requirements specified in the European regulation as well as in the national requirements for opacimeters can be classified into two categories:

a) checks against smoke or gas having an opacity measured with a reference opacimeter, and the

b) use of optical density filters representative of a gas of known opacity. Both methods mentioned here only consider the effects of the dynamics of free acceleration in a narrow way. But the effective (physical and electrical) response time and the dampening are absolutely decisive for the result (see ISO 11614 [[xix]]). Obviously, the second option (optical density filters) is not applicable to the calibration of the novel instrumentation. On the other hand, the low sensitivity of currently applicable opacimeters imposes limitations with respect to the lowest emission levels against which the novel instrumentation can be checked. Furthermore, an accepted reference instrument doesn't exist, as is the case for the reference opacimeter defined in Germany.

Alternative metrics to be employed for the calibration of the novel instrumentation include gravimetrically determined Particulate Matter (PM) and “non-volatile” Particle Number (PN), both of which are regulated. The gravimetrically determined mass of Particulate Matter however, is not a well-defined measurand. Its definition is rather based on the sampling and measurement procedure employed and, of course, on the emission source, all of which are difficult to be reproduced for calibration purposes. The gravimetric calibration causes two problems: The standard gravimetric method is designed for longer sampling times and larger smoke volumes (steady state or accumulated probe), and the uncertainty for gravimetric measurements increases at lower concentrations.

Condensation Particle Counters (CPCs) used to measure the Particle Number, have the advantage of being very sensitive and even being capable of detecting single particle counts. Their use as a reference instrument has the additional advantage of providing a link to the work conducted in WP1. It is important though to investigate whether, and to what extent, the correlations between PN, opacity and the properties measured by the novel instrumentation depend on the calibration material and the underlying size distribution.

It is also important to consider that (owing to the long service life of the vehicles) future periodic inspection procedures will have to apply both to conventional high-emitting diesel vehicles and their latest DPF-equipped counterparts. The particle number emissions from conventional diesels (on the order of 10^8 cm^{-3}) may be more than three orders of magnitude higher compared to DPF-equipped diesels. It is not clear whether it would be feasible for a single candidate instrument to cover this large concentration range. Yet, if the purpose of a periodic inspection check is to identify malfunctions of the emission control devices, and particularly cracks in the Diesel Particulate Filter (DPF), different procedures may be appropriate for non-DPF- and DPF-equipped diesels.

Conclusively, two reference metrics have been identified, namely: Particle Number and opacity. The device under test needs to be assessed through comparison to Particle Number- and/or opacity-based instrumentation. Checks should be performed over a large range of number concentrations (10^5 to 10^8 cm^{-3}) and light extinction coefficients (0.01 m^{-1} to 3.0 m^{-1}) using a range of size distributions (polydisperse aerosols) typical for light-duty diesel exhaust (geometric mean diameter of 50 to 100 nm and geometric standard deviation of 1.6 to 1.9) [[xxxii]]. Calibration aerosols should contain at least graphite or soot (CAST or other combustion sources).

The performance characteristics to be investigated include measurement accuracy, sensitivity and dynamic response. All of these need to be assessed for the complete measurement system, including all necessary sample conditioning devices. Special attention needs to be given to investigating a potential effect of the sample pressure and temperature on the instrument response. Furthermore, the possibility of verifying the novel instruments will be evaluated.

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