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Measurement Procedure for Evaluation of Full-Flow, Light-Extinction Smokemeter Performance—SAE J1157

SAE Recommended Practice
Approved August 1976

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PREPRINT

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MEASUREMENT PROCEDURE FOR EVALUATION OF FULL-FLOW, LIGHT-EXTINCTION SMOKEMETER PERFORMANCE—SAE J1157

SAE Recommended Practice

Report of Automotive Emissions Committee approved August 1976.

Purpose

This SAE Recommended Practice is for evaluating the performance of full-flow, light-extinction type smokemeters (opacimeters) designed to measure the exhaust smoke opacity from diesel engines. It is intended to serve as a design and development guide for instrument manufacturers and as a performance evaluation procedure to be used by engine laboratories for determining by a standard method, the performance of developed smokemeters.

Scope

The detailed test procedures outlined in this recommended practice consist of two general types of tests. These tests are of the bench type and a full scale engine type test, which exposes the smokemeter to the environment (exhaust gases) that the meter ultimately must perform in if it is to be of practical use. The bench type tests consist of two general types. The first series of bench tests are used to assess the basic optical and electrical characteristics of the instrument. The second series of bench tests are used to evaluate the effect of a simulated operating environment (temperature, light, and vibration) on the smokemeter. Finally, performance limits for the various types of smoke-meters and for various smoke concentrations are established based on the bench and engine performance tests outlined above.

This recommended practice does not develop the various instrumental techniques for measuring smoke since these are contained in SAE Information Report - SAE J255 (1). The background data supporting this recommended practice is contained in References (2) and (3). SAE Recommended Practice J35 (4) contains guidelines for running engine tests with developed full-flow light extinction type smokemeters.

Background

Visible smoke emissions from diesel engines are measured in terms of the amount of light attenuated or transmitted by the emissions in the visible portion of the spectrum relative to the incident light. The percentage of light attenuated is defined as the opacity of the smoke emissions. The light transmitted is the transmittance (expressed as a ratio) of the smoke emissions. A plume that does not attenuate any incident light is invisible and will have a transmittance of 1.0 and an opacity of 0%. A plume that attenuates all the incident light is said to be 100% opaque and, therefore, it has an opacity of 100% and a transmittance of 0.0. An instrument that measures and monitors opacity or transmittance is referred to as an *opacity meter*, *transmissometer* or as an *opacimeter*. This recommended practice is written around full-flow, light-extinction type smokemeters since they are the only type of opacity meters that have the technical capability to accurately measure transient smoke levels. Sampling type light-extinction meters have inherent design limitations for accurate measurement of transient smoke concentrations.

Two important optical characteristics of opacity meters must be specified to obtain similar performance from instruments: the operating wavelength and light collimation of the instruments. The operating wavelength is important because fine particulates attenuate shorter wavelength radiation more than longer wavelengths. The light collimation is important because measurement of the true opacity of diesel smoke requires the exclusion of light scattered by the smoke from the measurement. Collimation requires an optical design that limits the light viewing and projection angles of the instrument. There are also a number of other electronic and mechanical design features that must be integrated into a properly designed and developed instrument. By experience it has been found that these performance characteristics can only be determined by laboratory tests. This recommended practice, therefore, outlines detailed bench and engine test procedures for use in developing operating performance characteristics of opacity meters. These tests are discussed in Sections 2 and 3. Design guidelines and performance specifications that quality meters should perform to under these bench and engine laboratory test procedures are outlined in Section 4. It is recognized that meters will in general be developed as

either *laboratory* or as *portable field* meters and that they would also be developed for different ranges of smoke opacity and in turn would have different sensitivities. Therefore, guidelines for the design of meters of various sensitivities are outlined and the bench and engine performance specifications have been developed for both types of meters, that is, *laboratory* and *portable field*.

Sections

The procedure is divided into the following sections:

1. Definition of Terms and Abbreviations
2. Bench Test Procedures
3. Engine Test Procedures
4. Smokemeter Design and Performance Considerations for Accuracy, Precision, and Convenience
5. Appendices A and B

1. Definitions of Terms and Abbreviations

1.1 Terms Used

1.1.1 Diesel Engine—Any compression ignition internal combustion engine, using the basic diesel cycle, that is, combustion results from the spraying of fuel into air raised in temperature by compression.

1.1.2 Diesel Smoke—Particles, including aerosols, suspended in the engine's gaseous exhaust stream which obscure, reflect, and/or refract light.

1.1.3 Opacity—That fraction of light transmitted (T) from a source which is prevented from reaching the observer or instrument receiver expressed in percent [Opacity = 100% (1-Transmittance)].

1.1.4 Smoke Density—The smoke density (K) of a plume is defined by the opacity (N) and the effective optical path length (L) in the following manner (Beer-Lambert Law):

$$K = -\frac{1}{L} \ln \left(1 - \frac{N}{100} \right).$$

K is also known as the optical absorption coefficient or extinction coefficient.

1.1.5 Optical Density—The optical density (D) of a plume or a filter is a logarithmic measure of the amount of light attenuated by the filter and is defined in the following manner: $D = \log_{10} (1/T)$.

1.1.6 Full-Flow Light-Extinction Opacimeter—An optical instrument designed to measure the opacity of the full-flow of the diesel exhaust gases passing through the optical unit.

1.1.7 In-Line Opacimeter—An optical smokemeter designed to be mounted directly in the exhaust system pipe.

1.1.8 End-of-Line-Opacimeter—An optical smokemeter designed to be mounted directly in the exit of the free plume over the open end of the exhaust pipe so that the free plume passes through the smokemeter's light path.

1.1.9 Effective Optical Path Length—The length of exhaust gases that the emitter light must pass through to reach the detector.

1.1.10 Laboratory Type Smokemeter—A smokemeter designed to be used primarily in a laboratory where accuracy and precision are more important than weight, size, and battery power.

1.1.11 Field Portable Type Smokemeter—A smokemeter designed to be used primarily in the field where weight, size, and battery power are more important than meter accuracy and precision.

1.1.12 Rated Brake Power—The power specified by the manufacturer for a given application at a given (rated) speed and as measured in accordance with SAE J270.

1.1.13 Rated Speed—The speed at which the manufacturer specifies the rated brake power of an engine.

1.1.14 Peak Torque Speed—The speed at which the engine develops maximum torque as stated by the manufacturer.

1.1.15 Intermediate Speed—The peak torque speed or 60% of rated speed, whichever is higher.

1.2 Abbreviations Used

°C — degrees Celsius
K — kelvin



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h – hour
 nm – nanometres
 AC – alternating current
 DC – direct current
 °F – degrees Fahrenheit
 R – Rankine
 hp – horsepower
 Hz – Hertz
 V – volts
 min – minute
 rpm – revolutions per minute
 % – percent
 s – second
 ms – millisecond
 mV – millivolts
 in – inch
 g – acceleration due to gravity = 32.2 ft/s² (9.81 m/s²)

2. Bench Test Procedures¹

2.1 Emitter and Detector Spectral Response

The purpose of this procedure is to evaluate the spectral characteristics of the emitter and detector used in the smokemeter².

2.1.1 *Set up the smokemeter* on a test bench, connect power supply to smokemeter, and allow instrument to warm up for at least 15 min or as recommended in the manufacturer's instructions.

2.1.2 *Set the zero* (clear) and full scale (opaque) adjustments.

2.1.3 *Check emitter spectral characteristics* by using a spectrophotometer or equivalent instrument, as per manufacturer's instructions. Be sure spectrophotometer is calibrated at the emitter mean wavelength. Record the emitter light intensity as a function of wavelength (λ).

2.1.4 *Plot percent* of relative output of the emitter as a function of wavelength. Compare this with the manufacturer's data. See Appendix A, Fig. A.1 for typical emitter output spectral response curves.

2.1.5 *From approximately* the same location as the emitter, shine the light from an incandescent lamp at the detector housing opening of the smokemeter. The incandescent lamp should be held at a constant color temperature (5137R or 2854K) by maintaining constant voltage to the lamp.

2.1.6 *Between the lamp and detector* insert a series of ten (10) narrow pass optical filters. These filters should be calibrated and certified, traceable to NBS standards for calibrating spectrophotometer instruments used to measure filter transmittance, to pass only the narrow band of light in the wavelength specified on the filter. The ten (10) filters should cover the response spectrum of the detector (300-800 nm wavelength). Each filter must have the same relative transmission and blocking characteristics at pass and block wavelengths as each other filter does. Record the detector output as a function of wavelength of light passed by the filters.³

2.1.7 *Plot the percent* of relative output of the detector as a function of light wavelength. Compare this with the manufacturer's data.

2.2 Calibration

The purpose of this test is to evaluate the linearity of the smokemeter using calibrated neutral density filters.

2.2.1 *Set up the smokemeter* on a test bench, connect power supply, and allow instrument to warm up for at least 15 min or as recommended in the manufacturer's instructions.

2.2.2 *Connect output* to a suitable voltage meter (or current) and strip chart recorder.

2.2.3 *Adjust zero* (clear) and full scale (opaque) adjustments.

2.2.4 *Observe and record zero drift* for a period of at least 5 min. Check full scale setting for drift. Do not proceed until stable operation is achieved.

2.2.5 *Insert a series* of at least five neutral density filters of ⁴10, 20, 40, 60, and 80% opacity perpendicular (or at angle specified by manufacturer) to the light path of the instrument at a point mid-way between the light

source and the detector. Record the opacity readings of the smokemeter and the readings from the voltage meter on a log sheet such as Table 1.

2.2.6 *Plot the smokemeter* opacity and the voltage meter readings as functions of the opacity of the neutral density filters such as shown in Figs. 1 and 2.

2.2.7 *Compute and plot* the instrument error with each filter as follows:

$$E_M = \text{Calibration Error} = N_M \cdot N_F$$

Where:

N_M = % Opacity indicated by the instrument meter

N_F = % Opacity value of the filter

$$E_L = \text{Linearity Error, \%}$$

$$= \frac{100}{V_C \cdot V_O} (V_M \cdot V_F)$$

$$= \frac{100}{V_C \cdot V_O} \left[V_M \cdot \frac{V_C \cdot V_O (100 - N_F) + V_O}{100} \right]$$

Where:

V_M = Voltage meter reading with a filter in the light path

V_F = Theoretical voltage for linear output

V_C = Voltage from smokemeter with light path clear

V_O = Voltage from smokemeter with light path opaque

Example:

Opacity of Filter, N_F = 45%

Meter reading with filter in light path, N_M = 48%

Output voltage with clear light path, V_C = 110 mV

Output voltage with opaque light path, V_O = 2 mV

Output voltage with filter in light path, V_M = 55 mV

Calibration Error:

$$E_M = N_M \cdot N_F = 48 \cdot 45 = +3\% \text{ at } 45\% \text{ Opacity}$$

Linearity Error:

$$E_L = \frac{100}{V_C \cdot V_O} \left[V_M \cdot \frac{V_C \cdot V_O (100 - N_F) + V_O}{100} \right]$$

$$= \frac{100}{108} \left[55 \cdot \frac{110 \cdot 2}{100} (100 - 45) + 2 \right]$$

$$= 0.925 \left[55 \cdot \frac{108}{100} (55) + 2 \right]$$

$$= 0.925 \left[55 \cdot (59.4 + 2) \right]$$

$$= 0.925 (55 \cdot 61.4) = -5.9\%$$

¹Slight changes in procedures 2.1, 2.2, 2.6, 2.7, and 2.9 may be necessary for folded beam and chopped beam instruments.

²For a discussion of emitter and detector characteristics and their effect on smoke measurement, see Appendix A.

³Some smokemeters use solid state detectors that are designed to respond only to the emitter light in which case they will not respond to the incandescent lamp.

⁴See Appendix B for filter performance characteristics and guidelines for specifying and calibrating filters.

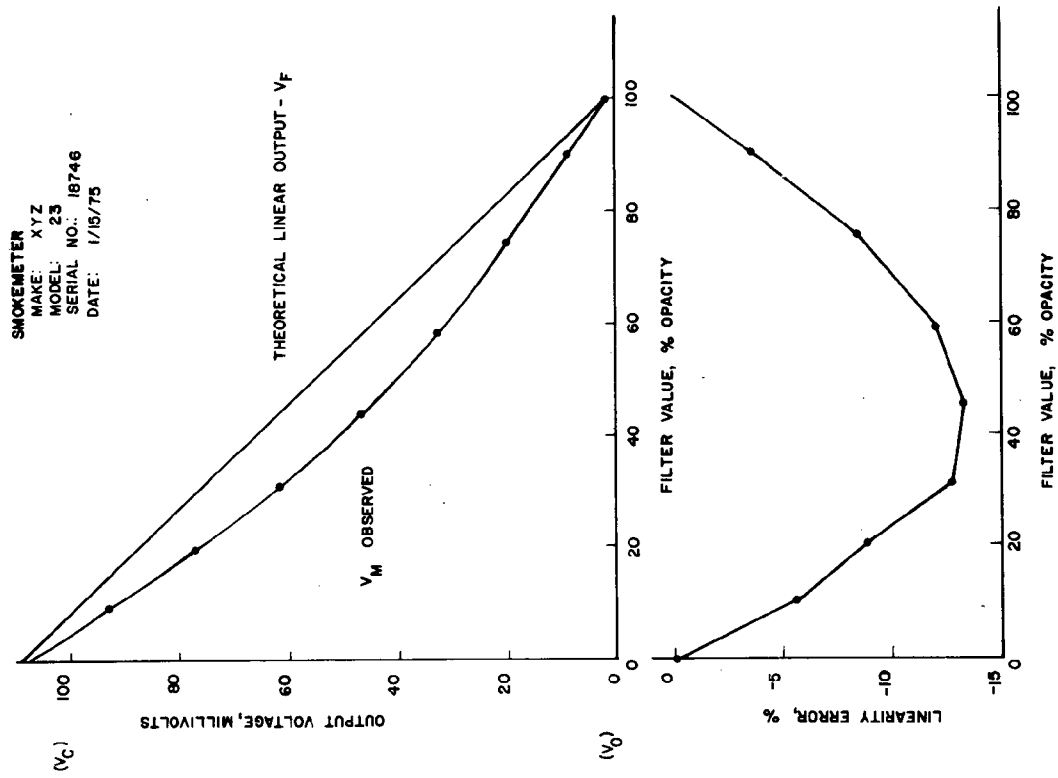


FIG. 2-VOLTAGE LINEARITY TEST

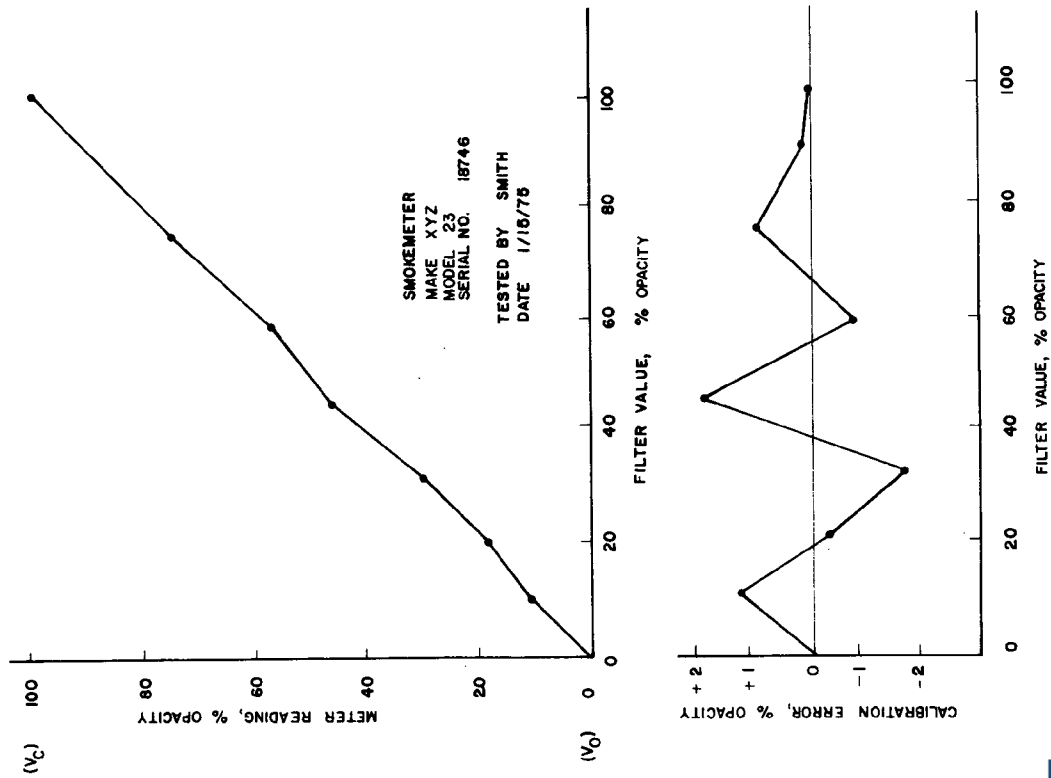


FIG. 1-SMOKEMETER CALIBRATION