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Diesel Engine Smoke Measurement

- 1. Scope**—Measurement of diesel smoke in an accurate and consistent manner has been a serious problem for engine and vehicle manufacturers, users, and agencies charged with enforcing smoke limits. Several instruments, based on different principles and using different scales, are commonly used. In addition to these, human observation and judgment are often used to relate smoke to a variety of standards.

The purpose of this SAE Information Report is to provide an understanding of the nature of diesel smoke, how it can be measured, and how the various measurement methods can be correlated. Except for defining the various types of smoke, the report deals solely with the steady-state measurement of visible, black smoke emitted from diesel engines.

For the benefit of those who wish to study various aspects of the subject in greater depth, a list of useful references is included in Section 2.

This document is divided into the following sections:

- 2. References
 - 2.1 Applicable Publications
 - 2.2 Related Publications
- 3. Definitions, Terminology, and Abbreviations
- 4. Procedure for Smoke Evaluation
 - 4.1 Instrumental
 - 4.2 Photographic
 - 4.3 Visual
- 5. Correlation of Steady-State Smoke Measurements

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2. References

2.1 Applicable Publications—The following publications form a part of this specification to the extent specified herein.

2.1.1 OTHER PUBLICATIONS

- Federal Registers, Vol. 33, No. 108, June 4, 1968; and Vol. 35, No. 219, Nov. 10, 1970. Washington, DC: U.S. Government Printing Office.
- F. J. Hills, T. O. Wagner, and D. K. Lawrence, "CRC Correlation of Diesel Smokemeter Measurements," Paper 690493 presented at SAE Midyear Meeting, Chicago, May 1969.
- A. W. Carey, Jr., "Steady-State Correlation of Diesel Smoke Meters—An SAE Task Force Report," Paper 690493 presented at SAE Midyear Meeting, Chicago, May 1969.
- W. D. Conner and J. R. Hodgkinson, "A Study of the Optical Properties and Visual Effects of Smoke Stack Plumes," Cooperative Study Project, Edison Electric Institute and U.S. Department of Health, Education, and Welfare.
- Bureau of Mines, Informational Circulars No. 8333 and 7718.
- 1974 EMA—Tech. Paper, "Ringelmann Numbers vs. Opacity," prepared by the Diesel Smoke Subcommittee of the Engine Manufacturers Association.
- "The Measurement of Diesel Exhaust Smoke," Motor Industry Research Association (MIRA) Report, 1965.
- "Evaluation of Test Methods for Diesel Engine Exhaust Smoke Measurement," Coordinating European Council (CEC), Fuels Committee Report, October 1968.

2.2 Related Publications—The following publications are provided for information purposes only and are not a required part of this document.

2.2.1 OTHER PUBLICATIONS

- R. D. Henderson, "Air Pollution and Construction Equipment," Paper 700551 presented at SAE Earthmoving Industry Conference, Peoria, IL, April 1970.
- Design and Test Specifications for Smoke Inspection Guides, U.S. Public Health Service (42 CFR Part 75).
- R. D. Fleming, W. F. Marshall, and R. W. Hurn, "The Fuel Factor in Diesel Emissions," Oral presentation made at SAE Midyear Meeting, Detroit, May 1970. (Note: Oral only, nonretrievable.)
- R. Burt and K. A. Troth, "Influence of Fuel Properties on Diesel Exhaust Emissions," Institute of Mechanical Engineers, London, November 1968.
- J. B. Durant and L. Eltinge, "Fuels, Engine Conditions, and Diesel Smoke," Paper 3R presented at SAE Annual Meeting, Detroit, January 1959.
- B. W. Millington and C. C. J. French, "Diesel Exhaust—A European Viewpoint," SAE Transactions, Vol. 75 (1967), Paper 660549.
- R. C. Schmidt, A. W. Carey, and Roy Kamo, "Exhaust Characteristics of the Automotive Diesel," SAE Transactions, Vol. 75 (1967), Paper 660550.
- M. Vulliamy and J. Spiers, "Diesel Engine Exhaust Smoke—Its Measurement, Regulation, and Control," Paper 670090 presented at SAE Automotive Engineering Congress, Detroit, January 1967.
- C. O. Miller, "Diesel Smoke Suppression by Fuel Additive Treatment," Paper 670093 presented at SAE Automotive Congress, Detroit, January 1967.
- W. F. Marshall and R. W. Hurn, "Factors Influencing Diesel Emissions," SAE Transactions, Vol. 77 (1968), Paper 680528.
- Ralph C. Stahman, George D. Kettredge, and Karl J. Springer, "Smoke and Odor Control for Diesel Powered Trucks and Buses," SAE Transactions, Vol. 77 (1968), Paper 680443.
- R. G. Kolb and I. O. Kamm, "Diesel Air Pollution Study for New Jersey State Department of Health," Stevens Institute Report, June 1967.
- H. E. Styles, J. Vrebos, and J. Lawther, "Public Health Aspects of Air Pollution from Diesel Vehicle," World Health Organization Report, 1967.

John R. Kinosian, John A. Maga, and John R. Goldsmith, "The Diesel Vehicle and its Role in Air Pollution," California Department of Public Health Report to California Legislature, December 1962.
 "Measuring Diesel Exhaust Smoke," Ethyl Corp. Technical Notes, May 1968.
 "1962 CRC Smokemeter Tests," CRC Report 371, August 1963.
 "1967 CRC Diesel Smokemeter Calibration Tests," CRC Report 421, June 1969.
 "Aircraft Gas Turbine Engine Exhaust Smoke Measurement," SAE Aerospace Recommended Practice, May 1970.
 SAE J1157, "Measurement Procedure for Evaluation of Full Flow, Light-Extinction Smokemeter Performance," August 1976.
 1977 CRC Report, "A Laboratory Comparison of In-Line and End-of-Line Full Flow Diesel Smoke Opacity Meters," prepared by Smoke Panel of CRC-APRAC Program Group on Composition of Diesel Exhaust.

3. Definitions, Terminology, and Abbreviations—The following apply to definitions, abbreviations, and/or terms as used in this document:

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

3.1.1 BLACK SMOKE—Particles composed of carbon (soot), usually less than 1 µm in size, which have escaped the engine's combustion process.

3.1.2 WHITE AND BLUE SMOKE—Particles composed of essentially colorless liquid (droplets) which reflect and refract the observed light.

NOTE—The observed color results from the refractive index of the liquid in the droplets and the droplet size. White smoke is usually due to condensed water vapor or liquid fuel droplets. Blue smoke is usually due to droplets resulting from the incomplete burning of fuel or lubricating oil.

3.2 Instrumental Smoke Measurement—Any technique which involves direct measurement of an intrinsic property of the smoke without recourse to human judgment or comparison.

3.2.1 LIGHT EXTINCTION METHOD—Any technique which involves a measurement of the amount of light which fails to penetrate a column of smoke.

3.2.2 FILTERING METHOD—Any technique which involves a measurement of the amount of soot particles collected by passing exhaust gases through a filtering medium.

3.3 Visual Smoke Measurement—A measurement technique which relies upon human observation of an engine's smoke plume to rate that plume's appearance against an established scale of blackness or opacity (usually a gray scale on either a transparent or opaque white base).

3.4 Photographic Smoke Measurement—A measurement technique which relies upon an instrumental or visual comparison of the photographic image of a smoke plume with an established scale of blackness or opacity to determine the opacity of the original smoke plume.

3.5 Transmittance (T)—That fraction of light transmitted from a source, through a smoke-obscured path, which reaches the observer instrument receiver, expressed in percent (%),

$$\left(T = 1 - \frac{\text{opacity}}{100} \right) \quad (\text{Eq. 1})$$

3.6 Opacity (N)—That fraction of light transmitted from a source which is prevented from reaching the observer or instrument receiver, expressed in percent (%), $N = 100 (1 - T)$.

3.7 Beer-Lambert Law—For purposes of diesel smoke measurement an equation expressing the relationship between the opacity of a smoke plume, the effective optical path through the plume, and the opacity of the smoke per unit path length, may be used:

$$T = \frac{\text{Transmitted light}}{\text{Incident Light}} = e^{-KL} \quad (\text{Eq. 2})$$

and

$$N = 100(1 - e^{-KL}) \quad (\text{Eq. 3})$$

3.8 Absorption Coefficient—The absorption coefficient, K , (or m^{-1}), of a plume is defined in the following manner, a form of the Beer-Lambert Law:

$$K = -\frac{1}{L} \ln\left(1 - \frac{N}{100}\right) \quad (\text{Eq. 4})$$

where L is expressed in meters, m .

3.9 Effective Optical Path Length—The length of light beam between the emitter and the detector that is intersected by the exhaust stream, corrected for nonuniformity due to density gradients and fringe effects.

3.10 Abbreviations

- °C = degrees Celsius
- °F = degrees Fahrenheit
- % = percent
- m = meters
- N = opacity, %
- e = base of natural logarithms
- K = absorption coefficient (smoke density), m^{-1}
- L = effective path length through the smoke (meters)
- T = transmittance
- $\ln$ = natural log

4. Procedure for Smoke Evaluation

4.1 Instrument Methods for Smoke Measurement—Instruments for measuring diesel smoke may be classified generally as follows:

- a. Opacimeter, Full-Flow Type—Measures opacity of the full smoke plume. Can be either the exhaust stack (in-line) or at the outlet of the stack (end-of-line) type.
- b. Opacimeter, Sampling Type—Measures the opacity of a portion of the exhaust gas which has been extracted from the exhaust pipe and passed through a measurement chamber of standardized size.
- c. Filtering Method—Smoke soot particles are collected on a filter medium as a sample of the exhaust is forced through. The filter may be evaluated by comparison with standards, by photoelectric reflectance measurement methods, or by determining the mass of the sample.

A representative example of these general types of instruments will be described. With the exception of the direct soot measurement systems, each is commercially available.

4.1.1 OPACIMETER, FULL-FLOW TYPE

4.1.1.1 *End-of-Line Opacimeter*

4.1.1.1.1 Introduction—An example of this type is the USPHS (EPA) Diesel Smokemeter (Figure 1), developed by the U.S. Public Health Service.

The light source and photocell are located on opposite sides of the smoke plume, a few inches from the open end of the exhaust pipe (Figure 2). Output of the photocell may be read remotely on the calibrated milliammeter or by an optional chart recorder. The meter furnished with the instrument may be calibrated in either 0 to 100% light transmittance or opacity. The unit can be battery operated and requires a clean supply of compressed air, which is used as an air curtain to keep the light source and photocell free of soot. Calibration is accomplished by blocking the light beam for 100% opacity and by clean air (remove from plume or shut engine down) for zero capacity. Calibration between 0 and 100% can be established with neutral density filters which should be referenced to NIST standards. The instrument system is sensitive to smoke density and the effective optical path length (diameter of smoke plume). Therefore, it is important to define the location of the meter above the stack and the stack diameter when comparing readings with other smokemeters. Changes in opacity due to path length differences may be calculated by using the Beer-Lambert Law.

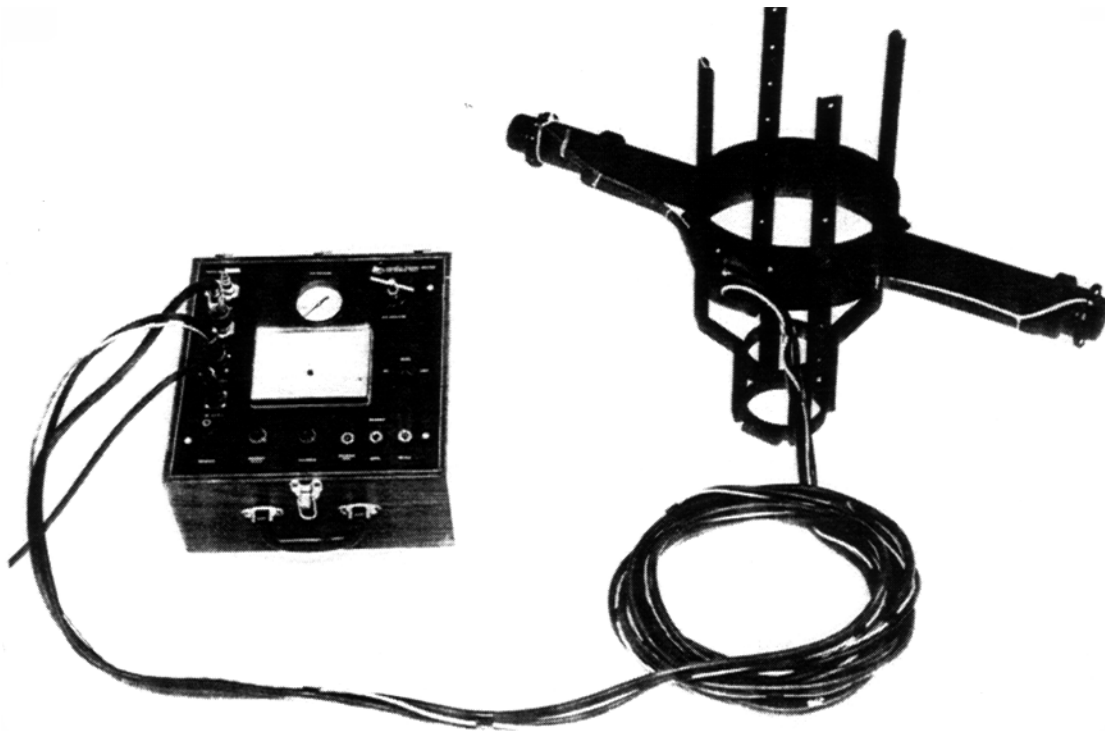


FIGURE 1—USPHS (EPA) DIESEL SMOKEMETER

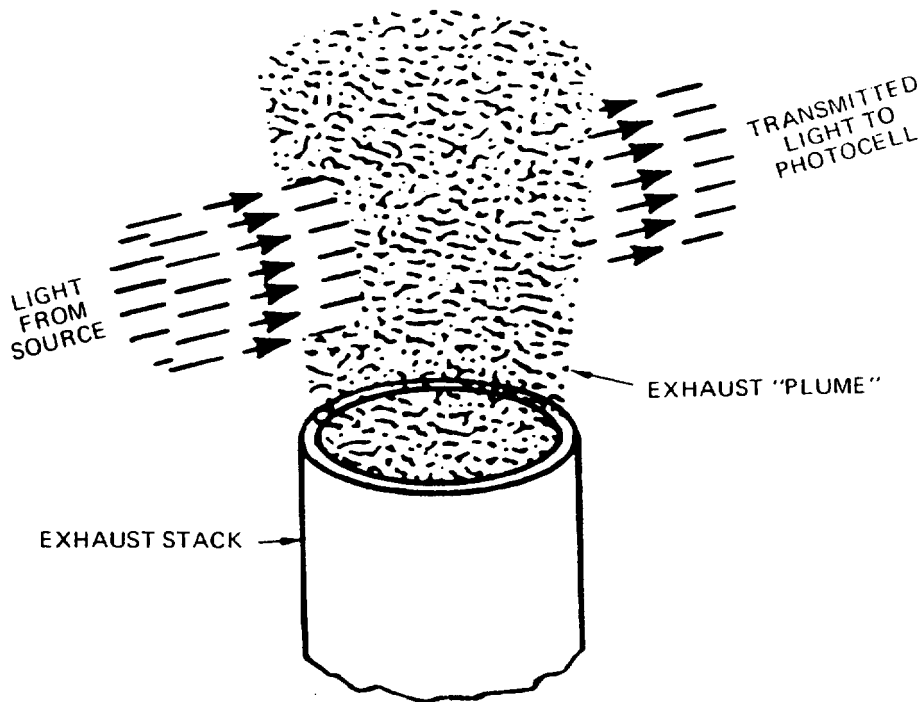


FIGURE 2—METHOD OF OPERATION OF FULL-FLOW TYPE OPACIMETER

4.1.1.1.2 Specific Operating Precautions

- a. Do not rigidly mount the optical unit on the engine exhaust pipe. Engine vibration can shake the lamp filament which may register as noise on recorders. It may also shake lenses and loosen other mechanical and electrical components within the unit.

If adaptation of the instrument for portable vehicular operation is attempted, several modifications are suggested:

1. General—Shock mount the photocell, solder all electrical connections, strengthen mechanical parts, and use a frosted lamp to minimize the effect of filament vibration.
 2. Power Supply—Inverters, gasoline engine generators, or batteries may be used to power the optical unit and recorder. Vehicle electrical systems should not be used for power, since voltage fluctuations result in instrument zero shift.
 3. Air Supply—Bottled nitrogen or vehicle brake air supply, properly filtered and dried, may be used.
- b. The open stack, a relatively critical location for the optical unit, and the need to calibrate on clean air are features not particularly well suited to laboratory engine testing. Hoods or funnels have been used successfully, but the particular exhaust gas disposal system must be considered when this smoke meter is used. The smoke ventilation systems should not influence the shape of the exhaust plume. Exhaust noise and room ventilation also must be considered when testing indoors.

CAUTION—Exhaust stacks larger than 5 in in diameter should not be used.

4.1.1.2 In-Line Opacimeter

4.1.1.2.1 Introduction—An example of this type is the Celesco Model 107 Smokemeter (Figure 3). The light source (pulsed light-emitting diode) and detector (photodiode) are located on opposite sides of the smoke plume in the sensor mounts as shown. Output from the photodiode may be read remotely on the microammeter or by an optional recorder. The unit requires a clean supply of compressed air, flowing through the sensor mounts to keep the light source and detector free of soot. Water-cooled sensor mounts are used for temperature isolation (recommended for ambient temperatures above 49 °C (120 °F). Calibration is accomplished by electrically blocking the detector circuit (to minimize source diode thermal drift) for 100% opacity and clean air (shut engine down) for zero opacity. Calibration between 0 and 100% can be established with natural density filters which should be referenced to NIST standards.

This instrument system is sensitive to smoke density and the effective optical path length.

4.1.1.2.2 Specific Operating Precautions

- a. Mount the meter sensor unit in a straight section of pipe downstream of any curved sections.
- b. Provide clean purge air to the photocell and light source to avoid soot contamination.
- c. For in-line meters used with laboratory engines and sufficiently large inertia dynamometers, a hot zero can be attained by running the engine at high speed, then closing the throttle, and removing the load simultaneously to allow the engine to decelerate against the dynamometer inertia. This allows a period of approximately 2 to 5 s of no smoke while the engine is purging the stack with clean air during which time the meter can be zeroed.

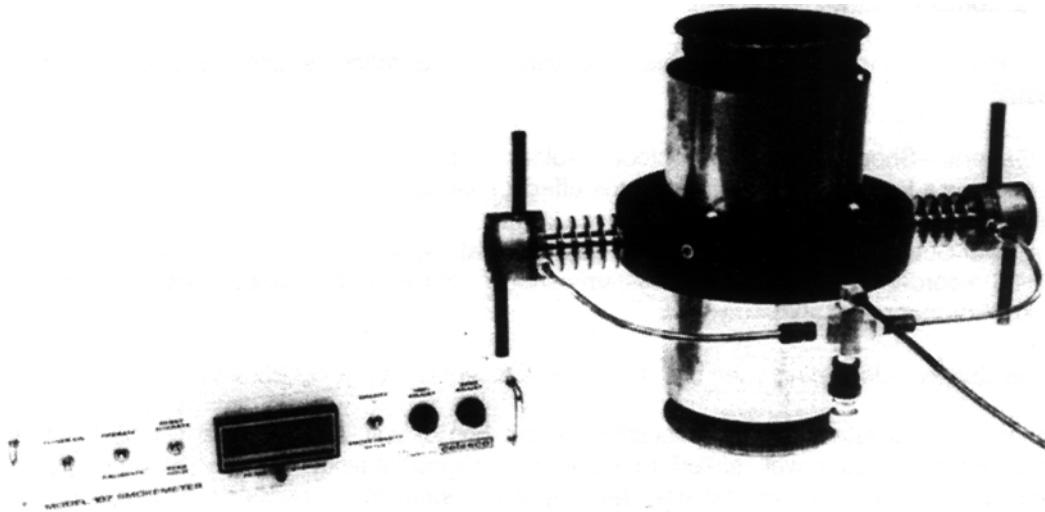


FIGURE 3—CELESCO MODEL 107 SMOKEMETER

4.1.1.3 General Operating Precautions

- a. The compressed air supply must be free of oil, water, and dirt, any of which may obscure light and introduce error in the readings. For oil contaminated lines, it is necessary to thoroughly flush the supply air system back to the air filters.
- b. Chart recorder response characteristics can affect the reading obtained. The Federal Register (2.1.1) specifies recorder response for certification testing. This is especially important for transient smoke tests, and it should be established that the readout instrumentation used has proper response for transient work. The optical system of the opacimeter is extremely fast, and with suitable recorders (light beam type of an oscilloscope) the smoke puffs from individual cylinders of a multicylinder engine may be observed.
- c. Since neutral density (ND) filters used in the calibration of opacimeters are not truly neutral, the filters should be calibrated at the same mean effective wavelength as the meter.

4.1.2 OPACIMETER, SAMPLING TYPE

4.1.2.1 *Introduction*—Figure 4 shows the Hartridge MK3 smokemeter, an example of this type.

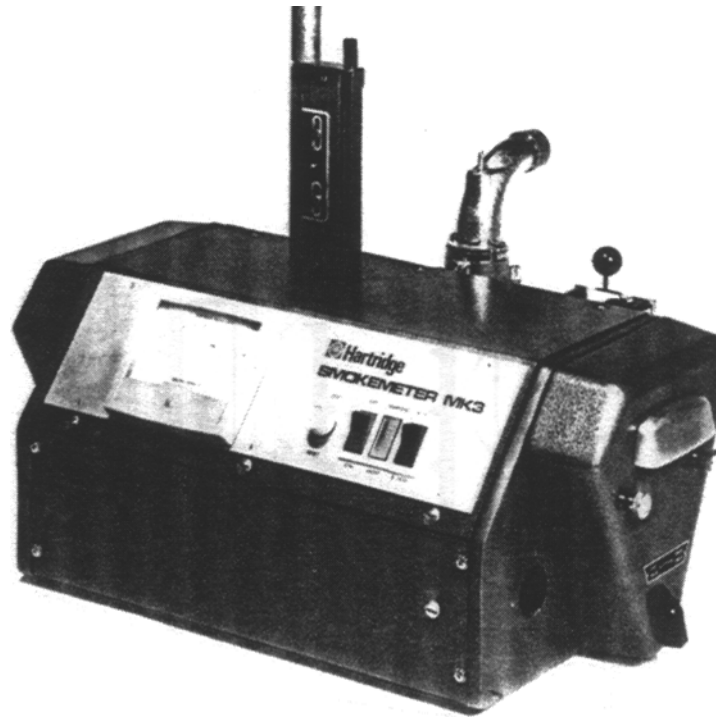


FIGURE 4—HARTRIDGE MK3 SMOKEMETER

Figure 5 illustrates the operating principle which involves measuring the opacity of a portion of exhaust gas continuously flowing through the sample tube. Zero reference is achieved by a switching arrangement which utilizes a second tube containing clean air, free of smoke. An internal electric fan purges the instrument case (of smoke) and clears soot from the light source and photocell. The calibrated milliammeter reads in units from 0 (clear) to 100 (completely opaque). Since the smoke tube length is fixed and known, these readings can be related to smoke measurements made with other instruments by means of the Beer-Lambert law. The smoke reading is not affected by exhaust pipe diameter. Transient response is limited to the time required to fill the sampling tube (transport time approximately 0.2 to 0.6 s) and by the length of tube which serves to deliver the sample.