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Snap-Acceleration Smoke Test Procedure for Heavy-Duty Diesel Powered Vehicles

RATIONALE

This Test Procedure had a minor error which has been corrected. The document is now being Stabilized because it no longer represents best practice for emissions evaluation. This procedure should only be used if there is no better alternative.

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Foreword—This Document has not changed other than to put it into the new SAE Technical Standards Board Format.

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1. **Scope**—This SAE Recommended Practice applies to vehicle exhaust smoke measurements made using the Snap-Acceleration test procedure. Because this is a non-moving vehicle test, this test can be conducted along the roadside, in a truck depot, a vehicle repair facility, or other test facilities. The test is intended to be used on heavy-duty trucks and buses powered by diesel engines. It is designed to be used in conjunction with smokemeters using the light extinction principle of smoke measurement.

This procedure describes how the snap-acceleration test is to be performed. It also gives specifications for the smokemeter and other test instrumentation and describes the algorithm for the measurement and quantification of the exhaust smoke produced during the test. Included are discussions of factors which influence snap-acceleration test results and methods to correct for these conditions. Unless otherwise noted, these correction methodologies are to be considered an integral part of the snap-acceleration test procedure.

- 1.1 **Purpose**—This document provides a procedure for assessing smoke emissions from in-use vehicles powered by heavy-duty diesel engines. Testing conducted in accordance with this procedure, in combination with reference smoke values, is intended to provide an indication of the state of maintenance and/or tampering of the engine and fuel system relative to the parameters which affect exhaust smoke. The procedure is expected to be of use to regulatory and enforcement authorities responsible for controlling smoke emissions from heavy-duty diesel-powered vehicles, and to heavy-duty vehicle maintenance and repair facilities. However, the procedure as written does not replicate the federal engine certification smoke cycle, and is intended to identify gross emitters. Regulatory agencies using this procedure must establish pass/fail criteria since SAE by-laws prohibit assignment of such criteria.

2. References

- 2.1 **Applicable Publications**—The following publications form a part of this specification to the extent specified herein. Unless otherwise specified, the latest issue of SAE publications shall apply.

- 2.1.1 SAE PUBLICATIONS—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J1349—Engine Power Test Code—Spark Ignition and Compression Ignition—Net Power Rating
SAE J1995—Engine Power Test Code—Spark Ignition and Compression Ignition—Gross Power Rating

- 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 SAE PUBLICATIONS—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J255a—Diesel Engine Smoke Measurement
SAE J1243—Diesel Emission Production Audit Test Procedure

- 2.2.2 ISO PUBLICATION—Available from ANSI, 11 West 42nd Street, New York, NY 10036-8002.

ISO CD 11614—Apparatus for the Measurement of the Opacity of the Light Absorption Coefficient of Exhaust Gas from Internal Combustion Engines

- 2.2.3 FEDERAL PUBLICATION—U. S. Government, DOD SSP, Subscription Service Division, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094

Code of Federal Regulations (CFR), Title 40, Part 86, Subpart I—Emission Regulation for New Diesel Heavy-Duty Engines: Smoke Exhaust Test Procedure

2.3 Other Publications

Procedures for Demonstrating Correlation Among Smokemeters

3. Definitions

- 3.1 **Diesel Smoke**—Particles, including aerosols, suspended in the exhaust stream of a diesel engine which absorb, reflect, or refract light.
- 3.2 **Transmittance (T)**—The fraction of light transmitted from a source which reaches a light detector.
- 3.3 **Opacity (N)**—The percentage of light transmitted from a source which is prevented from reaching a light detector. See Equation 1.

$$\text{Opacity \%} = 100 * (1 - \text{Transmittance}) \quad (\text{Eq. 1})$$

- 3.4 **Effective Optical Path Length (L) or (EOPL)**—The length of the smoke obscured optical path between the smokemeter light source and detector. Note that portions of the total light source to detector path length which are not smoke obscured do not contribute to the effective optical path length.
- 3.5 **Smoke Density (K)**—(also known as “Light Extinction Coefficient” and “Light Absorption Coefficient”) A fundamental means of quantifying the ability of a smoke plume or smoke containing gas sample to obscure light. By convention, smoke density is expressed on a per meter basis (m-1). The smoke density is a function of the number of smoke particles per unit gas volume, the size distribution of the smoke particles, and the light absorption and scattering properties of the particles. In the absence of blue or white smoke, the size distribution and the light absorption/scattering properties are similar for all diesel exhaust gas samples and the smoke density is primarily a function of the smoke particle density.
- 3.6 **Beer-Lambert Law**—A mathematical equation describing the physical relationships between the smoke density (K) and the smoke parameters of transmittance (T), and effective optical path length (L). Because smoke density (K) cannot be measured directly, the Beer-Lambert equation is used to calculate (K), when opacity (N) and EOPL (L) are known.
- 3.7 **Smoke Opacimeter**—A type of smokemeter designed to measure the opacity of a plume or sample of smoke by means of a light extinction principle.
- 3.8 **Full-Flow End-of-Line Smokemeter**—A smokemeter which measures the opacity of the full exhaust plume as it exits the tailpipe. The light source and detector for this type of smokemeter are located on opposite sides of the smoke plume and in close proximity to the open end of the tailpipe. When applying this type of smokemeter, the effective optical path length is a function of the tailpipe design.
- 3.9 **Sampling Type Smokemeter (Also called Partial Flow Smokemeter)**—A smokemeter which continually samples a representative portion of the total exhaust flow and directs it to a measurement cell. With this type of smokemeter, the effective optical path length is a function of the smokemeter design.
- 3.10 **Smokemeter Measurement Zone**—The effective length between the smokemeter light source and light detector through which exhaust gases pass and interact with the smokemeter light beam.

3.11 Smokemeter Response Time—See 6.3 and Appendix A.

3.12 Smokemeter Linearity—A measure of the maximum absolute deviation of values measured by the smokemeter from the reference values.

4. Special Notes and Conventions

4.1 The term smokemeter is a broad term which applies to all smoke-measuring devices regardless of the smoke-sensing technique employed. Throughout this document, the term smokemeter will refer only to opacimeter type smokemeters.

4.2 To fully describe the light obscuration properties of a smoke sample (i.e., smoke density), opacity (N) must always be associated with an EOPL. Whenever specific smoke opacity values are referenced in this document, the associated effective optical path length is understood to be 0.127 m (5 in).

5. Snap-Acceleration Test—The complete Snap-Acceleration process consists of five phases. These phases are:

- a. Vehicle Preparation and Safety Check
- b. Test Preparation and Equipment Set-up
- c. Driver Familiarization and Vehicle Preconditioning
- d. Execution of the Snap-Acceleration Test
- e. Calculation and Reporting of Final Results

5.1 Vehicle Preparation and Safety Check—Prior to conducting the snap-acceleration test, the following items must be completed:

- a. If the vehicle is equipped with a manual transmission, the transmission must be placed in neutral and the clutch must be released.
If the vehicle is equipped with an automatic transmission, the transmission must be placed in the park position, if available, or otherwise in the neutral position.
- b. The vehicle wheels must be chocked or the vehicle must be otherwise restrained to prevent the vehicle from moving during the testing.
- c. Vehicle air conditioning should be turned off.
- d. If the engine is equipped with an engine brake, it must be deactivated during the snap-acceleration testing.
- e. All devices installed on the engine or vehicle which alter the normal acceleration characteristics of the engine and have the effect of temporarily lowering snap-acceleration test results, or preventing the test from being successfully completed, shall be deactivated prior to testing.
- f. Verify the speed-limiting capability of the engine governor using the following procedure:
With the engine at low idle, slowly depress the engine throttle and allow the engine speed to gradually increase toward its maximum governed high idle speed. As the engine speed increases, carefully note any visual or audible indications that the engine or vehicle may be of questionable soundness. If there are no indications of problems, allow the engine speed to increase to the point that it is possible to verify that the speed-limiting capability of the governor is functioning. Should there be any indication that the speed-limiting capability of the governor is not functioning, or that potential engine damage, or unsafe conditions for personnel or equipment may occur, the throttle should immediately be released and the snap-acceleration testing of the vehicle shall be aborted.
- g. The vehicle should be inspected for exhaust leaks. Severe leaks in the system may cause the introduction of air into the exhaust stream which may cause erroneously low test results.
- h. Users must be cautioned regarding the observance of blue or white smoke in the exhaust. Blue smoke can be an indicator of unburned hydrocarbons (possible oil burning or malfunctioning nozzle), and white smoke can be an indicator of water vapor (possible internal coolant leaking conditions).

5.2 Test Preparation and Equipment Set-up

- 5.2.1 **AMBIENT AIR TEST CONDITIONS**—Ambient air conditions can affect snap-acceleration smoke test results. To ensure reliable results, the correction factors in Appendix B should be applied to snap-acceleration testing results to account for normal changes in ambient conditions. However, these correction factors must be applied under the following conditions.
- Altitude—Greater than 457 m (1500 ft) above sea level.
 - Air Temperature—Above or below the range of 2 to 30 x °C (36 to 86 x °F).
 - Wind—Excessively windy conditions should be avoided. Winds are excessive if they disturb the size, shape, or location of the vehicle exhaust plume in the region where exhaust samples are drawn or where the smoke plume is measured. The effect of wind may be eliminated or reduced by locating the vehicle in a wind-sheltered area or by using measuring equipment designs which preclude wind effects on the smoke in the measuring or sampling zones.
 - Dry Air Density—If the correction factors referenced in Appendix B are used, the useful range of dry air densities are: 0.908 to 1.235 kg/m³ (0.0567 to 0.0771 lbm/ft³). This range of dry air densities is based on air densities experienced during ambient conditions testing.
 - Humidity—No visible humidity (including fog, rain, and snow) in the region where exhaust samples are drawn or the smoke plume is measured. Some equipment designs preclude the effects of these conditions.
- 5.2.2 **SMOKEMETER INSTALLATION**—The smokemeter and other test equipment used for snap-acceleration tests shall meet the specifications of 6.1 through 6.5. The general installation procedures specified by the smokemeter manufacturer shall be followed when preparing to test a vehicle.

In addition, these special installation procedures shall be followed:

- If the test results are to be reported in units of smoke opacity, the rated power of the engine should be determined. The rated power is needed to define the standard effective optical path length used to correct the as-measured smoke opacity to standard conditions as described in Appendix C. The rated power should be available from the tune-up label fixed to the engine or from literature supplied to the owner by the engine manufacturer. In some cases, particularly under roadside test conditions, it may not be possible to readily determine the rated engine power. In these cases, it is recommended that the OD of the vehicle tailpipe section be determined and used as the standard effective optical path length for the purposes of the Beer-Lambert corrections described in Appendix C. If the rated engine power becomes available after the test is run, the test result should be recorrected as necessary using Equation C3 and the appropriate standard effective optical path length from Table C1. Sampling in or immediately downstream of bends such as curved stack outlets in the exhaust pipe may cause some variability between individual Snap-Acceleration cycle readings.
- For Full Flow End-of-Line Type Smokemeters—The axis of the smokemeter light beam shall be perpendicular to the axis of the exhaust flow. The centerline of the light beam axis should be located as close as possible, but in no case further than 7 cm (2.76 in) from the exhaust outlet. Appendix D provides additional guidance for smokemeter replacement. Determine the effective optical path length used to make the smoke measurements. For straight tailpipes of circular cross section, the effective optical path length is equal to the tailpipe ID, and for tubing construction can be reasonably approximated by the tailpipe OD. Appendix D provides guidance for determining the as-measured effective optical path length when irregular tailpipe configurations are encountered. The as-measured effective optical path length is required to convert measured smoke values to standard corrected smoke values using the procedures described in Appendix C.

- c. For Sampling Type Smokemeters—The probe of the sampling type smokemeter shall be inserted into the exhaust tailpipe with the open end facing upstream and into the exhaust flow. The clearance between the inside edge of the open end of the sample probe and the tailpipe wall must be at least 5 mm (0.197 in). Only the probe and sampling pipe, or tubing, specified by the manufacturer of the smokemeter shall be used for the smoke sampling. Manufacturer's recommendations regarding the length of the sample line shall be adhered to.
- d. Multiple Exhaust Outlets—When testing vehicles equipped with multiple exhaust outlets, such as dual exhaust systems originating from a single manifold or single pipe, it is normally not necessary to measure the smoke from each exhaust outlet. The following approach is suggested. If there is no discernible difference in the exhaust smoke exiting from each multiple exhaust outlet, the smoke should be measured from the exhaust outlet that provides the most convenient meter installation. A visual observation of one or more preliminary snap-acceleration test cycles should be sufficient to make this determination. Should there be a discernible difference in the smoke exiting from the multiple exhaust outlets, install the smokemeter and conduct the snap-acceleration test on the exhaust outlet that visually appears to have the highest smoke level.

5.2.3 A tachometer to measure the engine speed may be installed and calibrated per the manufacturer's recommendations. A tachometer provides useful data regarding idle RPM, maximum engine RPM, the time necessary for the operator to accelerate the engine from idle to maximum RPM, and the time the engine speed was held at maximum RPM. This information helps to ensure repeatability between test cycles.

5.3 Driver Familiarization and Vehicle Preconditioning

- 5.3.1 Prior to the preconditioning test, the vehicle should be operated under load for at least 15 min to ensure that the engine is warmed-up. Alternatively, vehicle water and oil temperature gages may be checked to verify that the engine is within its normal operating temperature range.
- 5.3.2 SNAP-ACCELERATION CYCLE—The vehicle operator shall be instructed on the proper execution of the snap-acceleration test sequence. It is of critical importance that the vehicle operator fully understand the proper movement of the vehicle throttle during the testing.

With the vehicle conditioned as in 5.1 and with the engine warmed-up and at low idle speed:

- a. The operator shall move the throttle to the fully open position as rapidly as possible.
 - b. The operator shall hold the throttle in the fully open position until the time the engine reaches its maximum governed speed, plus an additional 1 to 4 s.
 - c. Upon completion of the 1 to 4 s with the engine at its maximum governed speed, the operator shall release the throttle and allow the engine to return to the low idle speed.
 - d. Once the engine reaches its low idle speed, the operator shall allow the engine to remain at idle for a minimum of 5 s, but no longer than 45 s, before initiating the next snap-acceleration test cycle. The time period at low idle allows the engine's turbocharger (if so equipped) to decelerate to its normal speed at engine idle. This helps to reduce the smoke variability between snap-acceleration cycles.
 - e. Steps (a) through (d) shall be repeated as necessary to complete the preliminary snap-acceleration cycles and the snap-acceleration test cycles described in 5.3.3 and 5.4.2.
- 5.3.3 PRELIMINARY SNAP-ACCELERATION TEST CYCLES—The vehicle shall receive at least three preliminary snap-acceleration test cycles using the sequence described in 5.3.2. The preliminary cycles allow the vehicle operator to become familiar with the proper throttle movement, and also remove any loose soot which may have accumulated in the vehicle exhaust system during prior operation.

If smoke measurements are made during the preliminary cycles, the preliminary cycles can also provide the opportunity to check for proper operation of the smoke measurement system, and to check if the test validation criteria of 5.4.4 can be met. In this case, the data-processing unit and the smokemeter zero and full scale should first be set according to 5.4.1 and 5.4.2.

5.4 Execution of the Snap-Acceleration Test

5.4.1 DATA PROCESSING UNIT SET-UP—Before snap-acceleration testing can proceed, the smokemeter data processing unit must be properly set up. The operating instructions supplied by the processing unit manufacturer should be consulted for specific set-up procedures; however, the following functional steps must be accomplished.

- a. If a multi-mode test system is used, the appropriate mode for snap-acceleration testing must be selected.
- b. The desired smoke output units (opacity or smoke density) must be selected.
- c. If the Beer-Lambert corrections as described in Appendix C are to be performed within the data-processing unit, values must be supplied for the standard and as-measured effective optical path lengths if opacity output is desired and for the as-measured effective optical path lengths if smoke density output is desired. Appendices C and D provide guidance in determining these input values.
- d. If a red LED smokemeter light source is used and light source wavelength corrections are to be performed within the data-processing unit, the appropriate selections must be made to trigger these calculations (see Appendix C).
- e. If the ambient condition corrections described in Appendix B are to be performed automatically by the data-processing unit, the appropriate ambient parameters must be input.
- f. Any additional test identification information consistent with the needs of the test program and capabilities of the data-processing unit should be supplied at this time. Normally this would include the test date, test operator, vehicle identification, and other such information.

5.4.2 SMOKEMETER ZERO AND FULL SCALE—Prior to conducting smoke measurements, the zero and full scale readings of the smokemeter shall be verified. (Some meter systems may automatically perform the zero and full scale checks. For other meters, this sequence will need to be done manually.) Should optional recording devices be part of the test set-up, this equipment should also be checked for proper operation and calibration.

- a. Smokemeter Warm-up—Prior to any zero and/or full-scale checks or adjustments, the smokemeter shall be warmed up and stabilized according to the manufacturer's recommendations. If the smokemeter is equipped with a purge air system to prevent sooting of the meter optics, this system should also be activated and adjusted according to the manufacturer's recommendations.
- b. Smokemeter Zero—With the smokemeter in the Opacity readout mode, and with no blockage of the smokemeter light beam, adjust the readout to display $0.0\% \pm 1.0\%$ opacity.
- c. Smokemeter Full Scale—With the smokemeter in the Opacity readout mode, and all light prevented from reaching the detector, adjust the readout of the smokemeter to display $100.0\% \pm 1.0\%$ opacity.

NOTE—For Smokemeter readouts in units of Smoke Density (K).

Smoke density (K) is a calculation based upon opacity and EOPL. The opacity scale offers two truly definable calibration points, namely 0% opacity and 100% opacity. The upper end of the smoke density scale is infinite, which makes this point on the K scale undefined. Because of this, the preferred method to set the zero and full scale of the meter when measuring in either smoke density (K) or opacity (N) units is to set the meter to the opacity readout mode and make the zero and full-scale adjustments as described in 5.4.2 (a) to (c). The smoke density would then be correctly calculated based upon the measured opacity and, of course, the EOPL, when the meter is returned to the smoke density readout mode for testing.

However, if this technique is not possible, it is acceptable to set the zero and span of the smokemeter in units of smoke density (K) with the use of a neutral density filter of known value. Should this be the case, the smokemeter zero and span shall be set as follows:

- d. Smokemeter Zero—With the smokemeter in the Smoke Density (K) readout mode, and with no blockage of the smokemeter light beam, adjust the readout to display $0.00 \text{ m}^{-1} \pm 0.10 \text{ m}^{-1}$.
- e. Smokemeter Span (If required by the smokemeter manufacturer)—With the smokemeter in the Smoke Density (K) readout mode, place a neutral density filter of known value between the light emitter and detector. The neutral density filter shall meet the accuracy requirements of 6.2.10 and have a known nominal value in the range of 1.5 to 5.5 m^{-1} . Adjust the smokemeter readout to display the filter nominal value, $\pm 0.10 \text{ m}^{-1}$.

NOTE—Neutral density calibration filters are precision devices and can easily be damaged during use. Handling should be minimized and, when required, should be done with care to avoid scratching or dirtying of the filter.

- 5.4.3 SNAP-ACCELERATION TEST CYCLES—Within 2 min of the execution of the preliminary snap-acceleration cycles, conduct three snap-acceleration test cycles, actuating the vehicle throttle in the manner and sequence described in 5.3.2 (a to e).

Determine the corrected maximum 0.5 s average smoke values for each of the three snap-acceleration cycles using the smoke data processing algorithms described in Appendices A and C.

At the conclusion of the test sequence, and where needed as per manufacturer's recommendation, determine the degree of smokemeter zero shift by eliminating all exhaust from between the smokemeter light source and detector and noting the smokemeter display.

- 5.4.4 TEST VALIDATION CRITERIA—The test results from 5.4.3 shall be considered valid only after the following criteria have been met.

- a. The post-test smokemeter zero shift values shall not exceed:
 - 1. $\pm 2.0\%$ opacity—For smoke measurements made in opacity.
 - 2. $\pm 0.15 \text{ m}^{-1}$ —For smoke measurements made in smoke density (K).
- b. The arithmetical difference between the highest and lowest corrected maximum 0.5 s average smoke values from the three test cycles shall not exceed:
 - 1. 5.0% opacity—For smoke measurements made in opacity.
 - 2. 0.50 m^{-1} —For smoke measurements made in smoke density (K).

- 5.4.5 INVALID TESTS—Should the smoke test data from 5.4.3 not meet the test validation criteria of 5.4.4, the following items should be checked as possible causes for the invalid test results:

- a. If the engine did not meet the operating temperature requirements, run the engine/vehicle under load for at least 15 min or until the vehicle oil and water temperature gages indicate that normal engine operating temperatures have been achieved. Return to 5.2.2 (Smokemeter Installation) and repeat the test sequence.
- b. If improper or inconsistent application of the vehicle throttle is suspected, re-instruct the vehicle operator as to the proper execution of the snap-acceleration test, especially the movement of the vehicle throttle, as detailed in 5.3.2. Continue on with the procedure at this point and repeat the preliminary test cycles and the snap-acceleration test sequence while observing the vehicle operator.
- c. Check the smokemeter, its installation on the tailpipe, and any support instrumentation for possible malfunctions. Correct as necessary and then return to 5.3.3 (Preliminary Snap-Acceleration Test Cycles), and repeat the test sequence.

- d. If the post-test smokemeter zero check was exceeded due to positive zero drift, the probable cause is soot accumulation on the smokemeter optics. It is recommended that the snap-acceleration test sequence be repeated and while doing so, the smokemeter zero may be readjusted during the low idle period between each of the snap-acceleration test cycles. If the measured low idle smoke level of the vehicle is less than 2.0% opacity or 0.20 m^{-1} smoke density, it is permissible to re-zero the meter while it remains exposed to the vehicle exhaust. If the idle smoke level exceeds these limits, it is necessary to discontinue exposure to exhaust before rezeroing the meter.
It is not necessary to complete an invalid test before employing the rezeroing technique discussed previously. If comparison of the low idle smoke readings shows an increasing trend from one test cycle to the next, sooting of meter optics can be suspected and the rezeroing technique can immediately be used.
If it is not possible to rezero the meter, the meter optics should be cleaned per the smokemeter manufacturer's recommended procedures and the test sequence should be repeated beginning at 5.3.3 (preliminary snap-acceleration test cycles). If zero drift and rezeroing difficulties persist, it is recommended that the meter purge air system (if so equipped) be checked for proper operation.
- e. If the procedure has been repeated in accordance with the requirements stated in 5.4.5 (a to d), and the test results still cannot be obtained that conform with the test validation criteria, then it is likely that the engine is in need of service.

5.5 Calculation and Reporting of Final Test Result—If the validation criteria of 5.4.4 are met, the data shall be deemed valid and the test complete. The average of the corrected maximum 0.5 s average smoke values from the three snap-acceleration test cycles shall be computed and reported as the final test result. (See Appendix A.)

6. Test Instrumentation Specifications—This section provides specifications for the required and optional test equipment used in the snap-acceleration test.

6.1 General Requirements for the Smoke Measurement Equipment—The snap-acceleration smoke test requires the use of a smoke measurement and data-processing system which includes three functional units. These units may be integrated into a single component or provided as a system of interconnected components. The three functional units are:

- a. A full-flow end-of-line or a sampling type smokemeter meeting the specifications of 6.2 through 6.4.
- b. A data-processing unit capable of performing the functions described in Appendices A and C.
- c. A printer and/or electronic storage medium to record and output the individual corrected maximum 0.5 s average smoke values from each snap-acceleration test cycle, and the final average snap-acceleration test result.

6.2 Specific Requirements for the Smoke Measurement Equipment

6.2.1 **LINEARITY**— $\pm 2\%$ opacity or $\pm 0.30 \text{ m}^{-1}$ density.

6.2.2 **ZERO DRIFT RATE**—Not to exceed $\pm 1\%$ opacity/hour.

6.3 Instrument Response Time Requirements

6.3.1 **OVERALL INSTRUMENT RESPONSE TIME REQUIREMENT**—The overall instrument response time (t) shall be: $0.500 \text{ s} \pm 0.015 \text{ s}$. It is defined as the difference between the times when the output of the smokemeter reaches 10% and 90% of full scale when the opacity of the gas being measured is changed in less than 0.01 s.

It shall include all the physical, electrical, and filter response times. Mathematically, it is represented by Equation 2. (See Appendix A for a more detailed methodology and an example calculation.)

$$t = \text{SQRT}(t_p^2 + t_e^2 + t_F^2) \quad (\text{Eq. 2})$$

where:

- t_p = The physical response time
- t_e = The electrical response time
- t_f = The filter response time

- 6.3.2 PHYSICAL RESPONSE TIME (t_p)—This is the difference between the times when the output of a rapid response receiver (with a response time of not more than 0.01 s) reaches 10% and 90% of the full deviation when the opacity of the gas being measured is changed in less than 0.1 s.

The physical response time is defined for the smokemeter only and excludes the probe and sample line. However, on some in-use smokemeter systems, the probe and sample line may significantly affect the overall response time of the system. If necessary, this shall be taken into account for any particular smokemeter system.

For full-flow type smokemeters, the response time is a function of the velocity of flow in the vehicle exhaust pipe and the path length across the detector (detector diameter). It can be assumed equal to a negligible 0.01 s. For sampling type smokemeters where the measuring zone is a straight section of pipe of uniform diameter, the physical response can be estimated by Equation 3:

$$t = 0.8 \cdot V / Q \quad (\text{Eq. 3})$$

where:

- Q = The rate of flow of gas through the measuring zone
- V = The volume of the measuring zone

For such instruments, the speed of the gas through the measuring zone shall not differ by more than 50% from the average speed over 90% of the length of the measuring zone.

For all smokemeters, if the physical response calculates greater than 0.2 s, then the response time shall be measured.

- 6.3.3 ELECTRICAL RESPONSE TIME (t_e)—It is defined as the time needed for the recorder output to go from 10% of the maximum scale to 90% of the maximum scale value when a fully opaque screen is placed in front of the photo cell in less than 0.01 s, or the LED is turned off. This is to include all of the effects of recorder output response time.
- 6.3.4 FILTER RESPONSE TIME (t_f)—Filtering of the smoke signal will be necessary on most smokemeters to achieve an overall response time of $0.500 \text{ s} \pm 0.015 \text{ s}$. Most smokemeters have a very fast electrical response time, but physical response times will vary from one device to the next depending on design and gas flow.

Appendix A specifies the recommended second-order digital filtering algorithm to be used.

- 6.3.5 DETERMINATION OF THE PEAK SMOKE VALUE—An algorithm in Appendix A shall be used to determine the reported peak exhaust smoke levels.

6.4 Smokemeter Light Source and Detector

- 6.4.1 LIGHT SOURCE—The light source shall be an incandescent lamp with a color temperature in the range of 2800 to 3250 °K, or a green light emitting diode (LED) with a spectral peak between 550 and 570 nm.

Alternatively, a red LED may be used provided that the appropriate light wavelength correction is made as described in Appendix C.

- 6.4.2 LIGHT DETECTOR—The light detector shall be a photocell or a photodiode (with a filter, if necessary). In the case of an incandescent light source, the detector shall have a peak spectral response in the range of 550 to 570 nm, and shall have a gradual reduction in response to values of less than 4% of the peak response value below 430 nm and above 680 nm.
- 6.4.3 The rays of the light beam shall be parallel within a tolerance of 3 degrees of the optical axis. The detector shall be designed such that it is not affected by direct or indirect light rays with an angle of incidence greater than 3 degrees to the optical axis.
- 6.4.4 Any method such as purge air which is used to protect the light source and detector from direct contact with exhaust soot shall be designed to minimize any unknown effect on the effective optical path length of the measured smoke (see C.5.1). For full-flow end-of-line smokemeters, the protection feature must not cause the smoke plume to be distorted by more than 0.5 cm. For sampling type smokemeters, the meter manufacturer must account for any effect of the protection feature in specifying the effective optical path length of the meter.
- 6.4.5 The sampling and digitization rate of the data processing units shall be at least 20 Hz (i.e., at least 10 data samples per 0.5 s interval). Additionally, the product of the data sampling time increment (seconds) and one half the data sample rate (Hz) rounded to the next higher integer value must be within the range of 0.500 to 0.510 s.

6.5 Specifications for Auxiliary Test Equipment

- 6.5.1 NEUTRAL DENSITY FILTERS—Any neutral density filter used in conjunction with smokemeter calibration, linearity measurements, or setting span shall have its value known to within 0.5% opacity or 0.04 m^{-1} . The filter's named value must be checked for accuracy at least yearly using a reference traceable to a national standard.
 - 6.5.2 If altitude correction (i.e., the altitude is greater than 457 m (1500 ft)) then:
 - a. Equipment used to measure barometric pressure must be accurate within $\pm 0.30 \text{ kPa}$ ($\pm 0.089 \text{ in-Hg}$)
 - b. Ambient dry bulb temperature must be accurate within $\pm 2 \text{ }^{\circ}\text{C}$ ($\pm 3.6 \text{ }^{\circ}\text{F}$)
 - 6.5.3 Measurement of the following parameters is optional; however, if measured, the specified accuracy requirements should be met:
 - a. Ambient Dry Bulb Temperature— $\pm 2 \text{ }^{\circ}\text{C}$ ($\pm 3.6 \text{ }^{\circ}\text{F}$)
 - b. Dew Point Temperature— $\pm 2 \text{ }^{\circ}\text{C}$ ($\pm 3.6 \text{ }^{\circ}\text{F}$)
 - c. Engine Speed— $\pm 100 \text{ rpm}$
 - 6.5.4 OPTIONAL RECORDING DEVICES—A supplemental chart recorder or other collection media may be used provided that the device(s) does not affect the smoke measurement.
7. **Smokemeter Maintenance and Calibration**—The smokemeter should be maintained and serviced per the manufacturer's recommendations. In addition to the zero and span adjustments to be made prior to each snap-acceleration test (5.4.2), the linearity of the meter response should be periodically checked as per manufacturer's recommendations in the range of measurement interest using neutral density filters meeting the requirements of 6.5.1. Non-linearities in excess of 2% opacity or 0.30 m^{-1} smoke density should be corrected prior to resuming testing with the meter.

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APPENDIX A

SECOND-ORDER FILTER ALGORITHM USED TO CALCULATE A
MAXIMUM 0.500 S AVERAGE SMOKE VALUE

A.1 Introduction—This appendix explains how to create and use the recommended Bessel low-pass digital filter algorithm in a smokemeter to filter out the high-frequency smoke readings which are produced during a snap-acceleration test. This appendix in particular describes the methodology used to design a low-pass second-order Bessel filter with a response time as needed for a particular smokemeter application. This appendix also describes the procedure for determining the final snap-acceleration test. Two example calculations detailing the selection of Bessel filter coefficients and their use are also provided in this appendix to illustrate the concepts more clearly.

The digital Bessel filter described in this appendix is a second-order (2-pole) low-pass digital filter algorithm. It is the recommended filter to be used for designing smokemeters with 0.500 s overall response times as required in 6.3. The Bessel filter type was chosen because it allows passage of all signals which do not change very much with time, but effectively blocks all signals with higher-frequency components. Its linear-phase characteristics also enable it to approximate a constant time delay over a limited frequency range. Transient waveforms can also be passed with minimal distortion when it is used as a running average type filter. A digital approach was chosen due to the relative ease of implementing a software algorithm in most smokemeters. However, analog Bessel filters using the appropriate electronic circuits may also be used.

A.2 Definitions

- B = Bessel parameter constant. It equals $[\text{Sqrt}(5)-1]/2$
- f_c = Bessel cutoff frequency used to control the filtered response
- t_e = Electrical response time of the smokemeter (seconds)
- t_F = Filter response time (seconds)
- t_{Fd} = Desired filter response time (seconds)
- t_p = Physical response time of the smokemeter (seconds)
- t_{10} = The test time when the output response to an input step response is equal to 10% of the step input
- t_{90} = The test time when the output response to an input step response is equal to 90% of the step input
- Δ_t = Time between two stored opacity values (i.e., sampling period (seconds))
- X_i = Bessel filter input at sample number (i)
- X_{i-1} = Bessel filter input at sample number (i-1)
- X_{i-2} = Bessel filter input at sample number (i-2)
- Y_i = Bessel filter output at sample number (i)
- Y_{i-1} = Bessel filter output at sample number (i-1)
- Y_{i-2} = Bessel filter output at sample number (i-2)

A.3 Designing a Bessel Low-Pass Filter—Designing the 0.500 s Bessel low-pass digital filter is a multistep process which may involve several iterative calculations to determine coefficients. This section provides a method for determining the desired amount of filtering for smokemeters with different electrical and physical response times, or different sample rates. Bessel filters can be designed to accommodate filter designs having response times ranging from 0.010 to 0.500 s, and digitization rates of 50 Hz and higher.

It is recommended that all Bessel filter calculations be performed in opacity units for the sake of consistency between smokemeters. If smokemeter output in units of density need to be reported, the Beer-Lambert law may be used to convert the final opacity results to density results, and perform any necessary stack size correction. This conversion should be done only after all Bessel filter equations have been performed due to the non-linearity of the Beer-Lambert law.