The Engineering Society For Advancing Mobility Land Sea Air and Space ®

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HIGHWAY VEHICLE PRACTICE

an American National Standard

SAE J35

Issued Jan. 1973
Revised Sept. 1988

Superseding J35 JAN73

Ø DIESEL SMOKE MEASUREMENT PROCEDURE

1. PURPOSE:

This SAE Recommended Practice provides a procedure for the assessment of transient smoke emissions from vehicular diesel engines using an engine dynamometer cycle which simulates on-highway operating conditions. While intended for engine development and evaluation, it is similar to the procedure which has been used for regulatory approval by the United States Government. In many areas, additional recommendations to improve test precision are offered.

2. SCOPE:

The recommended practice applies to the dynamometer test procedure which can be used to assess the smoke emission characteristics of vehicular diesel engines. In particular, this procedure describes the smoke test cycle, equipment and instrumentation, instrument checks, chart reading and calculation for evaluation of an engine's transient smoke emission characteristic. In addition, this procedure offers guidelines to be used in establishing correlation between full flow in-line and end-of-line opacimeters.

Since the type of test described here is transient in nature, a fast responding full flow opacimeter is required for the smoke measurements. Slow responding or sampling, or both, type instruments must not be used since they typically have excessive and variable response delays and do not provide an accurate measurement of an engine's transient smoke characteristics.

Note: It is recommended that whenever this procedure is cited, any additional or modified test conditions must be clearly reported.

3. SECTIONS:

The procedure is divided into the following sections:

1. Definitions of Terms and Abbreviations
2. Fuel Specifications
3. Smoke Emission Test
4. Smoke Test Cycle
5. Information to be Recorded
6. Equipment and Instrumentation
7. Instrument Checks
8. Data Analysis
9. Correlation Procedure for Full Flow Opacimeters

4. DEFINITION OF TERMS AND ABBREVIATIONS:

4.1 Terms Used:

4.1.1 Vehicular Diesel Engine: Any compression ignition internal combustion engine used to propel onland, nonrail, mobile equipment.

4.1.2 Diesel Smoke: Particles, including aerosols, suspended in the engine's gaseous exhaust stream which obscure, reflect or refract, or both, visible light.

4.1.3 Rated Brake Power: The maximum brake power output of an engine in kilowatts as measured at rated speed.

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

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

4.1.6 Intermediate Speed: The peak torque speed, provided that speed occurs between 60 and 75% of rated speed. If the peak torque speed is less than 60% of rated speed, intermediate speed means 60% of rated speed. If the peak torque speed is greater than 75% of rated speed, intermediate speed means 75% of rated speed.

4.1.7 Curb Idle Speed: The engine's low idle speed as specified by the manufacturer (with tolerances) depending on the predominant transmission application.

Manual Transmission: The manufacturer's recommended speed with transmission in neutral or clutch disengaged.

Automatic Transmission: The manufacturer's recommended speed with transmission in gear.

4.1.8 High Idle Speed: The engine's governed maximum speed that occurs during wide-open throttle and no-load conditions.

4.1.9 Full Load Power: The power produced, at the speed being considered, when the throttle control is placed in the maximum fuel position.

4.1.10 Opacity: That fraction of light transmitted from a source which is prevented from reaching the observer or instrument receiver expressed in percent [opacity = 100% (1 - transmittance)].

4.1.11 Smoke Opacimeter: An optical instrument designed to measure opacity of diesel exhaust gases. The full flow of exhaust gases passes through the optical path. Opacimeters, including in-line and end-of-line types, are described in SAE J255.

(The term opacimeter will be used throughout this practice in reference to smoke opacity measurement devices. Similarly, EOL and IL will be used to denote end-of-line and in-line types of opacimeters.)

4.1.12 Transmittance: That fraction of light transmitted from a source, through a smoke-obscured path, which reaches the observer or instrument receiver.

4.2 Abbreviations Used:

bhp - brake horsepower
dB - decibels
C - degrees Celsius
cS - centistokes
EOL - end of line
F - degrees Fahrenheit
Hg - Mercury
Hz - Hertz
I.D. - inside diameter
IL - in-line
in - inch
LSR - least squares regression
m - meter
min - minimum, minute
mm - millimeter
N - percent opacity
NA - naturally aspirated
NBS - National Bureau of Standards
Pa - pascal, kPa - kilopascals
rpm - revolutions per minute
s - second
T - transmittance
TC - turbocharged
W - Watts, kW - kilowatts
% - percent

5. FUEL SPECIFICATION:

5.1 The diesel fuels employed shall be clean and bright, with pour and cloud point adequate for operability. The fuels may contain non-metal additives as follows: Cetane improver, metal de-activator, anti-oxidant, dehazer, anti-rust, pour depressant, dye, and dispersant.

5.2 Since fuel properties can affect diesel smoke emissions, it is recommended for good comparability with other tests that fuel specifications comply with those in the current Code of Federal Regulations, Title 40, Part 86. Those specifications at the publishing date of this procedure are listed below. Any deviations of the test fuel properties from these specifications should be reported along with the test results.

Item	ASTM No.	No. 1 -- range --	No. 2
Cetane	D-613	48-54	42-50
Distallation	D-86		
IBP C(F)		166-199 (330-390)	171-204 (340-400)
10%		188-221 (370-430)	204-238 (400-460)
50%		210-249 (410-480)	243-282 (470-540)
90%		238-271 (460-520)	288-321 (550-610)
EP		260-293 (500-560)	304-349 (580-660)
Sulfur, %	D-120, D-2622	0.05-0.2	0.2-0.5
Gravity, API	D-287	40-44	33-37
Hydrocarbon composition			
Aromatics, %		8 min	27 min
Saturates, Olefins		Remainder	Remainder
Flash Point C(F)	D-93	49 (120) min	54 (130) min
Viscosity, cS	D-445	1.6-2.0	2.0-3.2

6. SMOKE EMISSION TEST:

Perform the following sequence of operations during engine dynamometer testing for smoke emissions:

6.1 Control the temperatures of 1) the air supplied to the engine to 25 ± 5°C and 2) the fuel pump inlet to 38 ± 5°C. It is recommended to test only when the observed barometric pressure is between 725 (96.7) and 785 (104.7) mm of Hg (kPa) in the test area. Note that smoke emissions are affected by the dry barometric pressure of the combustion air.

For TC engines at operating temperature, and at rated speed and full load power conditions, adjust the intake air restriction to within 25 mm of water of the maximum recommended by the manufacturer and the exhaust system back pressure to within 5 mm of Hg of the maximum recommended by the manufacturer. The measurement locations for intake and exhaust pressures should be as defined by the manufacturer. Measure and record observed power, fuel rate, engine speed, intake air temperature, fuel pump inlet temperature, intake air restriction, and exhaust back pressure.

For NA engines, the intake adjustment and measurement should be made at high idle conditions.

6.2 Optional: In addition to 6.1, operate the engine at the intermediate speed. Measure and record maximum observed torque, fuel rate, engine speed, intake air temperature, fuel pump inlet temperature, intake air restriction, and exhaust back pressure. Determine by experiment, if not previously determined, the preset loads required by the smoke test cycle (section 7).

6.3 Switch on the opacimeter. Allow for the meter circuit to stabilize per the manufacturer's instructions. Set the zero and span of the meter per 10.2 and 10.3.

The opacimeter should be mounted in accordance with 9.2 so that the natural flow of the exhaust gas stream is not disturbed by the meter, the mounting fixture, or any ventilation system.

6.4 Pass the exhaust flow through the opacimeter so that the opacity of the exhaust plume may be measured.

6.5 Operate the engine at rated brake power for 10 min or until the engine coolant, oil pressures and temperatures are stabilized.

6.6 Discontinue passing the exhaust gas stream through the meter. Check and reset the meter zero and span per 10.2 and 10.3. Check the linearity of the meter per 10.4.

6.7 Operate the engine in a manner required by the smoke test cycle (section 7). Continuously record smoke opacity and engine speed on a strip chart recorder or other appropriate instrument. The chart speed shall be at least 25 mm/min (1 in/min) during the idle mode and at least 200 mm/min (8 in/min) during the acceleration and lugging modes. If readings are taken by an automatic data acquisition system, readings shall be taken at least at 0.1 Hz at idle and 10 Hz during other modes.

6.8 Repeat the procedures as contained in 7.1 through 7.4 until the entire cycle has been run three consecutive times. If the acceleration and lugging modes have been performed within the tolerances specified in section 7, then the tests may be terminated at this time. If not, then the test procedure, beginning with the 10-min pre-conditioning described in 6.5, should be rerun until data has been obtained within the specified limits.

6.9 Within 1 min after completion of 6.8, recheck the zero and span of the smokemeter as described in 6.6. If either zero or span drift is in excess of 2% opacity, the test results should be considered invalid.

7. SMOKE TEST CYCLE:

Conduct each smoke emission test in accordance with the procedure specified in section 6. Follow the engine operating sequence per 7.1 through 7.4. Refer to the "Smoke Test Cycle" (chart 7.1) for locating real time events that indicate the beginning or ending, or both, of the elements of each mode and appear as letters A through J.

Note that if a motoring-absorbing dynamometer is used, motoring assist to overcome the dynamometer inertia is acceptable, but motoring in excess of -10 ft-lb (negative net torque) for more than 0.5 s to achieve speed targets is not permitted.

SMOKE TEST CYCLE

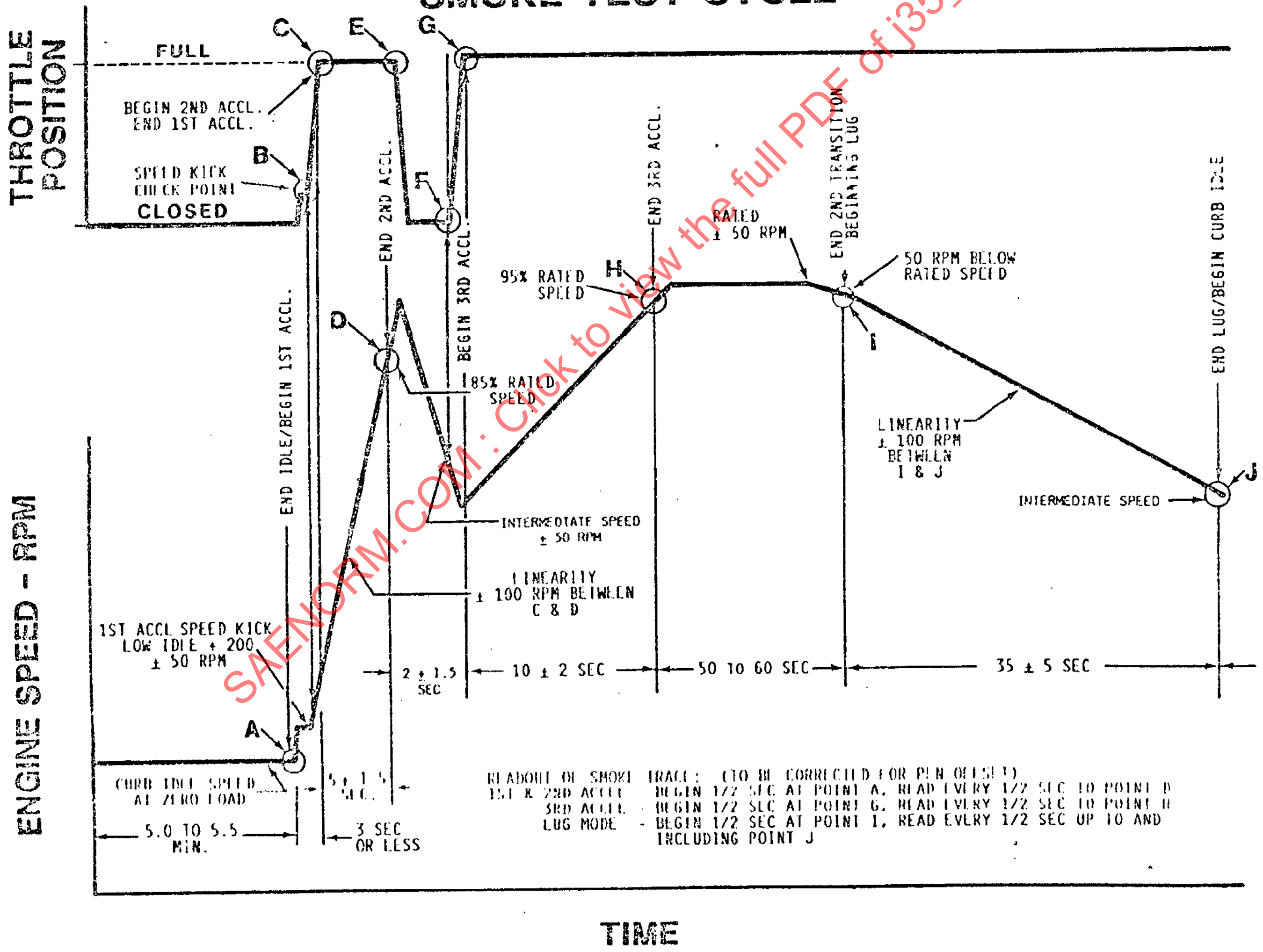

CHART 7.1

7.1 Idle Mode: Idle the engine for 5 - 5.5 min at the manufacturer's recommended curb idle speed. Dynamometer load may be applied to simulate an automatic transmission to achieve curb idle speed. Any other adjustments that cause idle speed to be altered for the purpose of simulating accessories are not allowed.

Idle mode begins following the preconditioning mode (6.5), or the lugging mode (7.4) designated J on the chart and ends at point A, the beginning of the acceleration mode. Idle speed should be held within specifications during the last 4 minutes.

7.2 Acceleration Modes: Consist of three separate sequences of engine accelerations with one deceleration between the second and third acceleration.

7.2.1 First Accel: Represented by points A, B, and C on the chart. Point A is where the first increase over curb idle speed occurs (typically defined as 5-10 rpm above the average observed idle speed). Point B is the event where the throttle begins to open to full position. Point C is where the throttle reaches a fully open position and must occur within 1 s of point B.

By partially opening the throttle, increase the speed to 200 ± 50 rpm above observed curb idle speed, measured at point B. The speed between points A and B should not exceed 50 rpm above that at point B. Total time measured between points A and C should not exceed 3 seconds.

7.2.2 Second Accel: Beginning at point C with full throttle, allow the engine to accelerate against inertia or a dynamometer load such that the engine speed increases to at least 85% of the rated speed. Point C is defined as 85% of rated speed. The acceleration between points C and D shall be kept linear within ±100 rpm, and the total time measured between points C and D shall be 5 ± 1.5 seconds.

7.2.3 Deceleration: Beginning at point E, rapidly move the throttle to, and hold in, the closed position. Point E is defined as any speed after point D (7.2.2), but is recommended not to exceed 95% of rated speed. Apply the required load to decelerate the engine to intermediate speed ±50 rpm, measured at point F which is the event where the throttle begins to reopen in preparation for the next accel mode (7.2.4). The fully opened throttle position is designated as point G. The deceleration time from point D to G shall be 2 ± 1.5 s for electric dynamometers only.

7.2.4 Third Accel: Beginning at point G, fully open throttle, the dynamometer load shall be adjusted to control the acceleration rate so that the engine speed increases to rated speed. The time duration between points G and H (defined as 95% of rated speed) shall be 10 ± 2 seconds.

Note: For best repeatability of results, all test-to-test acceleration (7.2.1, 7.2.2, 7.2.4) and deceleration (7.2.3) time durations should be kept consistent.

7.3 Rated Speed Mode: Represented by points H and I.

Immediately upon completion of the preceding (7.2.4) third accel mode at point H, adjust the dynamometer controls to permit the engine to develop rated brake power. The engine should operate within ±5% of rated brake power observed during the preconditioning mode (6.5) and be within ±50 rpm of rated speed during the last 10 s of this mode. Near the end of this mode, it is necessary to reduce engine speed by increasing the dynamometer load to prepare for the lugging mode as defined in 7.4. Point I defines the end of this mode and occurs when the speed is 50 rpm less than the manufacturer's specified rated speed. Total time between points H and I shall be 55 ± 5 seconds.

7.4 Lugging Mode: Beginning at point I, with the throttle remaining in the fully open position, adjust the dynamometer controls to gradually slow the engine down to intermediate speed over a period of 35 ± 5 s, marked by point J, as the end point of the lugging mode. The lug down speed between points I and J shall be linear within ±100 rpm. Point J is the beginning of the idle mode (7.1) for the next cycle.

7.5 Engine Unloading: Within 5 s of completing the preceding lugging mode (7.4), the engine and dynamometer controls shall be returned to the idle condition described in 7.1. The engine shall achieve idle speed within 60 s of point J. The zero and span of the opacimeters may be checked during the idle mode of each test and reset if necessary. If either the zero or span drift is in excess of 2% opacity, the test results are considered invalid and the test should be repeated.

8. INFORMATION TO BE RECORDED:

8.1 Record the following information in a test log for each smoke emissions test conducted:

8.1.1 Date, time of day, number of engine hours, test cell number, and observers.

8.1.2 Barometric pressure and combustion air humidity.

8.1.3 Maximum observed power, fuel rate, engine speed, fuel inlet temperature, intake air restriction, exhaust back pressure, and intake air temperature at rated speed.

8.1.4 Maximum observed torque, fuel rate, engine speed, intake air restriction, exhaust back pressure, and intake air temperature at peak torque speed.

8.1.5 Smoke opacimeter type and identifying number.

8.1.6 Exhaust pipe diameter at the point of measurement.

8.1.7 Calibrated and observed values of calibration filter(s).

8.1.8 Any other desired information.

8.2 Record or identify the following information on the recorder paper or input to the automatic data acquisition system at the time of each smoke emission test:

8.2.1 Test number.

8.2.2 Engine model and serial number.

8.2.3 Engine hours.

8.2.4 Test date and time of day.

8.2.5 Smoke opacimeter type and number.

8.2.6 Zero and span value of the calibration filter(s).

8.2.7 Real time signals of:

- Smoke and engine speed
- Throttle position, fully open and fully closed

8.3 Any other information as necessary to cross-reference the test log and smoke results should be noted.

9. <u>EQUIPMENT AND SMOKE MEASUREMENT INSTRUMENTATION</u>:

Use the following equipment and instruments for engine transient smoke measurements or opacimeter correlation tests. Either EOL or IL opacimeters may be used for the transient smoke measurements. For opacimeter correlation tests, refer to section 12 for additional guidelines.

9.1 An engine dynamometer with adequate characteristics to perform the test required by the smoke test cycle (section 7) must be used.

9.2 Provide an exhaust system of proper diameter for the engine being tested. The exhaust piping system must provide for adjustment of the exhaust back pressure, if specific back pressure levels are desired. If a muffler is needed, a conventional muffler of a size and type commonly used with the engine may be installed in the system.

9.2.1 <u>For EOL Opacimeters</u>:

a. Tailpipe - a minimum of 60 cm (24 in) of straight uniform diameter pipe must immediately precede the EOL opacimeter.

b. The I.D. of the tailpipe (section of pipe preceding the opacimeter) is determined by the rated brake power of the engine used during the test, as indicated in the table below.

Rated Brake Power		Tailpipe I.D. (last 60 cm)
75 kW or less	(100 bhp)	5.1 cm (2 in)
76-149 kW	(101-200 bhp)	7.6 cm (3 in)
150-224 kW	(201-300 bhp)	10.2 cm (4 in)
225 kW and above	(301 bhp)	12.7 cm (5 in)

9.2.1 (Continued):

c. An exhaust system whose length from the exhaust manifold to the exit is 4.6 ± 1.5 m (15 ± 5 ft) is recommended.

9.2.2 For IL Opacimeters: There should be at least 40 cm (16 in) of straight pipe before and after the opacimeter. The pipe should be the same I.D. as the opacimeter body with no sudden contractions or expansions in size near the opacimeter that could cause any changes in the exhaust flow direction or velocity.

9.3 Mount a full-flow, light extinction opacimeter in or on the exhaust system according to the provisions of 9.2. When dual exhaust systems are necessary, one should divide the engine rated power in half and use this value to determine the proper opacimeter-tailpipe size recommendations in 9.2.1.

9.3.1 The opacimeter must be installed and operated according to the meter manufacturer's recommendations. Care should be taken to assure that the purge air supply to the opacimeters is clean and dry.

Avoid installation of the opacimeter in areas where it may experience temperature extremes. Opacimeters, in general, are designed to handle the high temperatures of the engine exhaust flowing through them, but may not be able to handle the radiation from unanticipated outside sources such as exhaust manifolds, piping, and exhaust evacuation systems.

9.4 For EOL opacimeters, the optical unit of the meters shall be mounted radially to the exhaust pipe so that the measurement will be made at right angles to the axis of the exhaust plume. The optical axial centerline of the opacimeter should be located 12.7 ± 2.5 cm (5 ± 1 in) downstream from the end of the tailpipe. The full flow of the exhaust stream shall be centered between the emitter and detector apertures and centered on the light beam axis.

Avoid smoke measurements with EOL opacimeters at low ambient temperatures such as would occur outside during cold winter conditions. Experience has shown that opacity measurements can be confounded by condensed fuel or water vapor in the exhaust.

In addition, avoid smoke measurements under any conditions that may distort the smoke plume shape. This includes the possible plume distortion due to test area ventilation systems and exhaust evacuation systems, or under windy conditions, if the measurements are made outdoors.

9.4.1 Exhaust Evacuation Guidelines: It is important that efforts be made to insure that there is minimal distortion of the smoke plume in the area of the opacimeter. Failure to properly identify any exhaust evacuation system or wind or temperature, or both, influences on the plume will result in an undetectable error in the final results. When doing in-doors testing with an EOL meter, the following checks of the evacuation system should be made:

a. The flow capacity of the evacuation system must exceed the exhaust flow of the test engine. Based upon the shape, size and the amount of exhaust suction available, it is recommended that the exhaust evacuation system be able to ingest at least twice the actual engine exhaust volume flow due to the amount of ambient room air that becomes mixed with the exhaust between the tailpipe and the collection system.

b. Check the exhaust evacuation system capacity with the test engine operating at rated brake power. If any exhaust misses the evacuation system or is rejected by it, corrective action will be necessary to keep exhaust clear of the test area.

c. Check for plume distortion with the engine off (or at idle, depending upon the check method used), and with the evacuation system operating as it will be during the smoke measurement tests (see 9.4.2).

9.4.2 Detection of Plume Distortion: There are several methods that can indicate the amount of air currents around the EOL meter. With the engine off and the evacuation system operating, feeling around the EOL meter with moist bare hands or a 7-8 cm length of ribbon pinned to a pencil eraser can provide course indications of air movement that may influence smoke plumes, especially at engine idle conditions. A better indicator of air movements would be an anemometer or air velocity probe. Measurements with a device of this type should indicate that the air velocities around the opacimeter are below 1.2 m/s (4 ft/s).

The preferred analytical method to determine plume distortion requires the use of a CO_2 gas analyzer. With this method, the opacimeter light beam is replaced with a small diameter, 2-3 mm (1/8 in), steel tube with one small sampling hole near the center of the probe. The tube is connected to the CO_2 analyzer and used to sample the plume CO_2 concentrations. With the evacuation system and test engine operating, the sample probe is inserted in small increments into the exhaust plume. The CO_2 concentrations and the position of the sample hole relative to the opacimeter are noted. Traversing the entire plume will produce an exhaust CO_2 profile. Comparing this profile to another taken with the exhaust evacuation system at reduced flow, or at a larger gap between the tailpipe and the collection system, produces the means to determine the magnitude of any plume distortion.

9.5 Smoke opacity and engine speed are to be monitored continuously, using a strip chart recorder with the capability to meet the requirements of 6.7. Alternatively, an automatic data acquisition system with a minimum sampling rate of 10 Hz and resolution within 1% of full scale may be used.

9.6 The various components, opacimeters, electronic filters, and recorder, should comprise a system capable of data collection with the following limits:

9.6.1 The opacimeter is to be linear within ±1% opacity when calibrated to read from 0 to 100% full scale. The meter should have a resolution within 1% of full scale reading.

9.6.2 The engine speed reading is to be linear within ±30 rpm per second when calibrated to read from the low idle speed to rated engine speed. The reading should have a resolution within 1% of rated engine speed.

9.7. The use of general instrumentation for measuring engine speed, power, fuel rate, inlet air restriction, exhaust back pressure, and such pressures and temperatures while performing the tests as required in this part should not affect the recorded smoke values.

9.8 A separate low-pass electronic filter with the following performance characteristics may be installed between the opacimeter and the recorder, or any data acquisition system, to attenuate high frequency noise in the signal:

a. Three decibels point - 10 Hz
b. Insertion loss - 0 ± 0.5 dB
c. Selectivity - 12 dB per octave above 10 Hz
d. Attenuation - 27 dB down at 40 Hz min

If an automatic data collection system is used, the opacity signal should be filtered to match the recorder response characteristics.

10. <u>INSTRUMENT CHECKS</u>:

The instrument light source and electronics should be warmed up following the manufacturer's recommendations. In addition, instruments should be thermally stabilized by passing exhaust gas through them while operating the engine over practice test cycles.

For EOL opacimeters, during instrument checks, the meter may be positioned out of the path of the exhaust plume while the engine is in the idle mode (7.1). For IL opacimeters, the flow may be diverted from the opacimeter or the engine must be stopped after the practice runs to perform the calibration and instrument checks.

10.1 Follow good engineering practice in performing periodic opacimeter checks for cleanliness of the optical lenses, calibration checks of dynamometer speed and torque, and if used, recorder chart speed and linearity or automatic data acquisition equipment linearity.

10.2 After the instrument is thermally stable, set the span adjustment first by extinguishing the opacimeter light source and adjusting the output signal to indicate 100% opacity.

10.3 Adjust the zero control under conditions of no smoke. Check or set the automatic data acquisition equipment and chart recorder. Repeat span and zero checks until chart or data, or both, acquisition equipment repeat within 0.25% of correct reading without prior adjustment.

10.4 Insert calibrated neutral density filters, perpendicular to the light path and adjacent to the opening containing the light source. Filters should have a nominal opacity of 10, 20, and 40% and for best correlation, their calibration should be traceable to NBS. If readings deviate in excess of 1% of the calibrated value of the filter, corrective action should be taken.

11. DATA ANALYSIS:

Use the following procedure to determine the smoke opacimeter values:

11.1 Acceleration Smoke Value:

11.1.1 Locate the start of the first accel mode (point A, 7.2.1) and the end of the second accel mode (point D, 7.2.2) as one acceleration segment. Locate the beginning and ending of the third accel mode (points G and H, 7.2.4) as the second acceleration segment. If the smoke and engine speed data have been recorded on a strip chart recorder, it is usually necessary to account for pen off-set relationships between these two items in locating the interval check points.

11.1.2 Divide both of the acceleration segments into 1/2 s intervals beginning at the start of each segment. Disregard smoke values at the end of the segments for interval times less than 1/2 second. Determine the average smoke reading during each 1/2 s interval.

11.1.3 Locate and record the 15 highest 1/2 s readings during both acceleration segments of each cycle. Average the 45 readings from the three cycles. Record and designate this value as "A". ("A" represents the acceleration smoke characteristic of the engine.)

11.2 Lug Smoke Value:

11.2.1 Divide the lugging mode (interval between points I and J, 7.4) into 1/2 s intervals and determine the average smoke readings during each 1/2 s interval. Disregard smoke values at the end of this mode for any interval time less than 1/2 s.

11.2.2 Locate and record the 5 highest 1/2 s smoke readings during the lugging mode. Average the 15 readings from the three cycles. Record and designate this value as "B". ("B" represents the lugdown smoke characteristic of the engine.)

11.3 Peak Smoke Value:

11.3.1 Re-examine the 20 average 1/2 s values determined in 11.1.3 and 11.2.2 and from those, locate the 3 highest 1/2 s readings during each dynamometer cycle. Average the nine readings from the three cycles. Record and designate this value as "C". ("C" represents the peak smoke characteristic of the engine.)

12. CORRELATION PROCEDURE FOR FULL-FLOW OPACIMETERS:

12.1 Introduction: This section describes a method for correlating full flow opacimeters on the transient smoke test. This was written specifically with the intention of developing an EOL versus IL opacimeter correlation. However, it could be used to correlate any two (or more) full flow opacimeters, such as one IL to another IL opacimeter.

The correlation test method uses the transient smoke test procedure (section 7) to generate data. The opacimeters are connected in series on the exhaust pipe. Data from the meters are collected simultaneously during the transient smoke test.

It has been found experimentally that the Beer-Lambert law can be applied to opacimeters.[1] A mathematical correlation for converting the value of one opacimeter to the value, which would be obtained from another opacimeter, is developed from the Beer-Lambert law (12.6). This correlation is intended for usage with the 1/2 s average values used to calculate the A, B, and C smoke values of the transient smoke test.

The following sections describe the test set-up, opacimeter calibration, data collection, and data analysis methods:

12.2 General Test Set-Up: The equipment and instrument procedures contained in section 9 should be followed for opacimeter correlation tests.

12.2.1 The opacimeters should be installed in the exhaust system in series such that the two opacimeters view the same exhaust.

12.2.2 The meters should be as close as possible to each other in the exhaust stream. This is to minimize exhaust transport time between the meters and to assure that the composition of the exhaust does not change due to such factors as particle agglomeration or condensation that could possibly influence the light extinction properties of the exhaust. These factors are primarily a function of time, exhaust temperature, and density.

[1]Reference: (A. W. Carey, Jr., SAE Paper 690492, May, 1969)

12.2.3 If correlation tests between an IL meter and an EOL meter with several different tailpipe diameters are to be run, it is recommended that in addition to changing the tailpipe size, that the engine also be replaced with an engine with rated brake power conforming to the table listed in 9.2.1. This is because both EOL and IL opacimeters' plume shapes are affected by the exhaust velocity. Changing engine size with the tailpipes helps assure that the exhaust velocities will be within normal ranges.

12.3 Calibration: Instrument checks should be performed as defined in section 10.

12.4 Test Cycle: The test cycle used for correlation testing is the same as defined in section 7.

12.5 Data Collection: Data collection and analysis for correlation testing is the same as defined in section 11 with one exception. In order to minimize the difficulty of trying to time-align opacity data pairs, it is recommended to include the data collected during the deceleration defined in 7.2.3 in with all the other acceleration modes (7.2.1, 7.2.2, and 7.2.4).

12.6 Opacimeter Correlation Theory: Opacimeters correlate according to the Beer-Lambert law. This can be expressed mathematically as:

$$T = \exp(-KL) \qquad \text{eq 12.6.1}$$

$$\text{since } T = (1 - N/100) \qquad \text{eq 12.6.2}$$

$$N = 100\,(1 - \exp(-KL)) \qquad \text{eq 12.6.3}$$

T = transmittance
N = percent opacity
exp = base of natural logarithms
K = attenuation (or extinction) coefficient
L = path length through the smoke

For opacimeters subjected to the same smoke conditions, and having similar peak wavelength spectral response characteristics, the following opacity relationship can be derived:

$$N2 = 100\,(1 - (1 - N1/100)^{(L2/L1)}) \qquad \text{eq 12.6.4}$$

where N2, N1 = specific meter percent opacities
and L2, L1 = specific meter optical path lengths

The ratio of optical path lengths (L2/L1) can then be expressed as the ratio of the natural logarithms of each meter's transmittance.

$$L2/L1 = \ln(T2) / \ln(T1) \qquad \text{eq 12.6.5}$$

where ln = natural logarithm

or as a logarithmic function of opacities by:

$$L2/L1 = \ln(1-N2/100) / \ln(1-N1/100) \qquad \text{eq 12.6.6}$$