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Diesel Engine Emission Measurement Procedure

SAE Recommended Practice
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an American National Standard

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HIGHWAY VEHICLE PRACTICE

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Ø DIESEL ENGINE EMISSION MEASUREMENT PROCEDURE

1. PURPOSE OR SCOPE:

This SAE Recommended Practice is intended for use as a test procedure to determine the gaseous emission levels of diesel engines. Its purpose is to provide a map of an engine's emissions characteristics which, through use of the proper weighting factors, can be used as a measure of that engine's emission levels under various applications. The emission results for hydrocarbons, nitrogen oxides, carbon monoxide, and carbon dioxide are expressed in units of grams per kilowatt hour (grams/brake horsepower hour) and represent the mass rate of emissions per unit of work accomplished.

The emissions are measured in accordance with SAE Recommended Practices J177b, J215a, and J244 using non-dispersive infrared equipment for CO and CO_2, a heated flame ionization analyzer for HC, and a high performance NDIR or a chemiluminescence analyzer for NOx. All emissions are measured during steady-state engine operation. The mass rate of emissions is calculated (a) from the concentration in the exhaust gas and the exhaust flow for each mode or; (b) alternately, using a carbon balance method, from the concentration in the exhaust gas and the mass flow rate of fuel for each mode. If method (a) is used, CO_2 should be measured for data validation. The final emissions are calculated by dividing the summation of the weighted emission mass rates by the summation of the weighted brake power values for a cycle.

2. GENERAL PROVISIONS:

2.1 Definitions:

2.1.1 Diesel Engine: Any compression ignition engine.

2.1.2 Exhaust Emission: Any substance (but normally limited to pollutants) emitted to the atmosphere from any opening downstream from the exhaust port of the combustion chamber of an engine.

2.1.3 Rated Power: The maximum power output of an engine as stated by the manufacturer (in accordance with SAE J1349).

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

2.1.5 Intermediate Speed for U.S. On-Highway Applications: The peak torque speed, when that speed occurs between 60% and 75% of rated speed. If 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.

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

2.1.7 Curb Idle Speed: For heavy-duty diesel engines equipped with manual transmissions, curb idle means the manufacturer's recommended engine speed with the transmission in neutral or with the clutch disengaged. For heavy-duty diesel engines equipped with automatic transmissions, curb idle means the manufacturer's recommended engine speed with the automatic transmission in gear and the output shaft stalled.

2.1.8 Dynamometer Idle: For heavy-duty diesel engines equipped with automatic transmissions, dynamometer idle means the manufacturer's recommended engine speed without a transmission that simulates the manufacturer's recommended engine speed with a transmission and with the transmission in neutral.

2.1.9 Rated Torque: The maximum torque produced by an engine, as stated by the manufacturer.

2.1.10 Percent Load: The fraction of the maximum available torque at that engine speed.

2.2 Abbreviations: The abbreviations used in the recommended practice have the following meanings in both capital and lower case:

API	=	American Petroleum Institute
ASTM	=	American Society for Testing and Materials
α	=	Atomic hydrogen/carbon ratio of the fuel (approximately 1.8 for No. 2 diesel fuel)
Ø	=	Equivalence ratio (dry), that is, dry fuel air ratio (measured)/fuel-air ratio (stoichiometric)
BARO	=	Absolute barometric pressure, kPa (in Hg)
BHP	=	Brake power (horsepower)
BSCO	=	Brake specific carbon monoxide emissions, g/kW·h (g/bhp·h)
BSFC	=	Brake specific fuel consumption, g/kW·h (g/bhp·h)
BSHC	=	Brake specific hydrocarbon emissions, g/kW·h (g/bhp·h)
$BSNO_x$	=	Brake specific oxides of nitrogen emissions, g/kW·h (g/bhp·h)
DCO	=	CO volume concentration in exhaust, PPM (dry)
DCO_2	=	CO_2 volume concentration in exhaust, percent (dry)

2.2 (Continued):

DHC = Hydrocarbon volume concentration in exhaust, PPM (dry)
DKNO = NO volume concentration in exhaust, in PPM (dry and humidity corrected)
EIP = Absolute engine intake pressure, kPa (in Hg) = BARO-inlet restriction
f/a = dry fuel air ratio (measured) = (f/a) wet $\left(1 + \frac{G}{1000}\right)$
G = Humidity of the inlet air in grams of water per kilogram of dry air
K = Water-gas equilibrium constant = 3.5
K_{NO_x} = Humidity correction factor for oxides of nitrogen
K_W = Wet to dry correction factor
kW = Brake power (kilowatts)
M_C = Atomic weight of carbon (12.011)
$(M_C + M_H)$ = Mean molecular weight of fuel per carbon atom
M_{CO} = Molecular weight of CO (28.01)
M_F = Mass flow rate of fuel used in engine in grams/h
M_H = Atomic weight of hydrogen (1.008)
M_{NO_2} = Molecular weight of nitrogen dioxide (NO_2) (46.01)
P_V = Partial pressure of water vapor, kPa (in Hg)
T = Temperature of inlet air, °C (°F)
W_{CO} = Mass flow rate of CO in exhaust, grams/h
W_F = Weighting factor of U.S. on-highway applications (0.067 for modes 1, 7, and 13 and 0.08 for all other modes)
Whc = HC volume concentration in exhaust, PPMC (wet)
W_{HC} = Mass rate of HC in exhaust, grams/h
W_{NO_x} = Mass rate of NOx in exhaust, grams/h
Y = H_2O volume concentration in intake air

Where:

$$Y = \frac{P_V}{BARO - P_V}$$

3. ENGINE DYNAMOMETER TEST PROCEDURE:

3.1 Introduction: The test procedure consists of a prescribed sequence of engine operating conditions on an engine dynamometer with measurements of HC, NO_x, CO, and CO_2 during 13 steady-state modes with five modes at rated engine speed, five modes at an intermediate speed, and three modes at an idle speed.

3.2 Fuel Specification:

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

3.2.2 Fuel meeting the following specifications is currently recommended in the U.S. Highway regulations. Other fuels may be used, realizing that some fuel properties affect exhaust emissions results. If a fuel having a narrower specification range is desired to minimize the effect of fuel properties, the Department of Energy 2D Emissions Reference Fuel (which was first made available in October 1979) is recommended.

Item	ASTM Test No.	Range
Cetane number	D613	42-50
Distillation range	D86	
IBP, °C (°F)		171-204 (340-400)
10% Point, °C (°F)		174-238 (400-460)
50% Point, °C (°F)		243-282 (470-540)
90% Point, °C (°F)		288-321 (550-610)
EP, °C (°F)		304-349 (580-660)
Gravity, °API	D287	33-37
Total sulfur, %	D129	0.2-0.5
Hydrocarbon composition	D1319	
Aromatics, % min		27
Paraffins, naphthenes, olefins		Remainder
Flash point, °C (°F) min	D93	54 (130)
Viscosity, m^2/s (cst)	D445	$2.0-3.2 \times 10^{-6}$ (2.0-3.2)

3.3 Instrumentation:

3.3.1 Instrumentation shall be provided to measure the following engine operating data:

(a) Engine speed: rpm

(b) Torque: N·m (lb·ft)

(c) Mass fuel consumption: kg/min (lb/min)

(d) Observed barometer: kPa (in Hg)

(e) Water vapor pressure: kPa (in Hg)

(f) Intake air restriction: kPa (in H_2O)

(g) Exhaust back pressure: kPa (in Hg)

(h) Intake air temperature: °C (°F)

(i) Fuel temperature at pump inlet: °C (°F)

3.3.2 Instrumentation shall be provided to measure the engine intake air flow or exhaust flow and the concentration of CO, CO_2, NO_x, and HC in the exhaust as follows:

3.3.2.1 The determination of CO, CO_2, and NO_x concentrations shall be accomplished using sampling and analysis according to SAE J177b.

3.3.2.2 The determination of HC concentration shall be accomplished using sampling and analysis by a heated flame ionization detector method using SAE J215a.

3.3.2.3 The determination of intake air or exhaust flow shall be accomplished using SAE J244.

3.4 Test Conditions:

3.4.1 The following ranges of test conditions shall be maintained during exhaust emission testing:

3.4.1.1 Intake air temperature: 25 ± 5°C (77 ± 9°F)

3.4.1.2 Barometric pressure: 100 ± 3 kPa (29.6 ± 1 in Hg)

3.4.1.3 Fuel temperature at fuel pump inlet: 37 ± 5°C (99 ± 9°F)

3.4.1.4 Intake Restriction: The manufacturer's published maximum limit of air cleaner restriction.

3.4.1.5 Exhaust Restriction: Maximum permitted by the engine manufacturer as published in the sales and service literature. The restriction shall be met within ±0.70 kPa (±0.2 in Hg) while the engine is operating at rated power.

3.5 Test Procedure for Exhaust Emissions:

3.5.1 Break-In Procedure: The engine shall be run in accordance with the manufacturer's recommendation for break-in of an engine for engineering performance testing.

3.5.2 Pretest Conditioning Procedure: Operate the engine until emission rates have stabilized.

3.5.3 Emissions Measurement Procedure:

3.5.3.1 Operate the engine until pressures and temperatures are stabilized. Determine the maximum torque at the rated and intermediate speeds.

3.5.3.2 Operate the engine at the following modes:

Test Segment	Mode No.	Engine Speed	Observed Torque (Percent of Maximum Observed)	Time in Mode (Minutes) Minimum	Time in Mode (Minutes) Maximum	Maximum Cumulative Time (Minutes)
1	1	Curb-idle		4.5	6.0	
1	2	Intermediate	2	4.5	6.0	
1	3	.... do	25	4.5	6.0	
1	4	.... do	50	4.5	6.0	42
1	5	.... do	75	4.5	6.0	
1	6	.... do	100	4.5	6.0	
1	7	Curb-idle		4.5	6.0	
2	8	Rated	100	4.5	6.0	
2	9	.... do	75	4.5	6.0	
2	10	.... do	50	4.5	6.0	36
2	11	.... do	25	4.5	6.0	
2	12	.... do	2	4.5	6.0	
2	13	Curb-idle		4.5	6.0	

3.5.3.3 During each mode, the specified speed shall be held to within 50 rpm. Torque for each mode must be held at the specified value ±2% of the maximum torque observed.

(a) Read and record the following modal data during the last 2 min of each mode:

(1) Observed engine torque

(2) Observed engine rpm

(3) Intake air flow

(4) Engine intake air temperature

(5) Fuel flow

(6) Engine intake humidity (need not be taken for each mode unless the inlet air is humidity conditioned).

(b) Record the following for the full time in mode:

(1) Hydrocarbon analyzer output

(2) Carbon monoxide analyzer output

(3) Carbon dioxide analyzer output (if used)

(4) Nitrogen oxides ($NO + NO_2$) analyzer output

3.5.4 Analyzer Output Reading:

3.5.4.1 Locate the last 60 s of each mode and determine the average reading.

3.5.4.2 Determine the concentration of HC, CO, CO_2, and NO_x in each mode from the analyzer output reading (3.5.4.1).

3.5.4.3 Convert dry concentrations to wet per SAE J177b.

4. CALCULATIONS:

The test results for the emission test shall be derived through the following steps:

4.1 Calculate the mass emissions of HC, CO, and NO_x in grams/hour and the power for each mode as follows:

(a) $HC_{mass} = 0.0130 \times HC_{CONC}$ (ppm carbon) x exh. mass flow (lb/min)
$HC_{mass} = 0.0287 \times HC_{CONC}$ (ppm carbon) x exh. mass flow (kg/min)

(b) $CO_{mass} = 0.0263 \times CO_{CONC}$ (ppm) x exh. mass flow (lb/min)
$CO_{mass} = 0.0580 \times CO_{CONC}$ (ppm) x exh. mass flow (kg/min)

(c) $NO_x = 0.0432 \times NO_{xCONC}$ (ppm) x exh. mass flow (lb/min)
$NO_{x mass} = 0.0952 \times NO_{xCONC}$ (ppm) x exh. mass flow (kg/min)

(d) $kW_{obs} = rpm_{obs} \times torque_{obs}$ (N·m)/9549.3
$bhp_{obs} = rpm_{obs} \times torque_{obs}$ (lb·ft)/5252.1

4.2 Calculate the weighted average brake specific emissions for a cycle with the modal data from 4.1. A weighting for an average cycle which covers on-highway heavy-duty vehicles can be represented by a weighting factor of 0.20 for the average of the idle modes and 0.08 for all other modes. Calculate the brake specific emissions for HC, CO, and NO_x as follows:

$$BSHC = \frac{\Sigma(HC_{mass} \times W_F)}{\Sigma(kW \times W_F)} \quad \frac{g}{kW \cdot h}$$

$$BSHC = \frac{\Sigma(HC_{mass} \times W_F)}{\Sigma(bhp \times W_F)} \quad \frac{g}{bhp \cdot h}$$

$$BSCO = \frac{\Sigma(CO_{mass} \times W_F)}{\Sigma(kW \times W_F)} \quad \frac{g}{kW \cdot h}$$

$$BSCO = \frac{\Sigma(CO_{mass} \times W_F)}{\Sigma(bhp \times W_F)} \quad \frac{g}{bhp \cdot h}$$

$$BSNO_x = \frac{\Sigma(NO_{x mass} \times W_F)}{\Sigma(kW \times W_F)} \quad \frac{g}{kW \cdot h}$$

4.2 (Continued):

$$BSNO_X = \frac{\Sigma(NO_{X_{mass}} \times W_F)}{\Sigma(bhp \times W_F)} \quad \frac{g}{bhp \cdot h}$$

5. ALTERNATE CALCULATIONS:

5.1 Determine the exhaust species volume concentration for each mode.

5.2 Convert wet basis measurements to a dry basis by the following:

Dry concentration = (K_w) x Wet concentration

K_w is defined as follows:

$$K_w = 1 + \left[\frac{\alpha\left(\frac{DCO_2}{10^2} + \frac{DCO}{10^6} + \frac{2Y}{\emptyset}\left(\frac{DCO_2}{10^2} + \frac{DCO}{10^6} + \frac{Whc}{10^6}\right)\right)\left(1 + \frac{\alpha}{4}\right)}{2\ 1 + \left(\frac{\frac{DCO}{10^6}}{\frac{DCO_2}{10^2}\ K}\right)} \right]$$

5.2.1 Calculate Ø using the measured (f/a) entering the combustion chamber. If applicable, bleed air, etc., must be subtracted from the measured air flow.

5.2.2 Calculate a separate Y value for each test segment from the pretest segment data. Apply the Y value to the K_w equation for the entire test segment.

5.3 Compute the dry (f/a) as follows:

$$(f/a) = \frac{4.77\left(1 + \frac{\alpha}{4}\right)(f/a)_{stoich}}{\frac{1}{\bar{X}} - \left(\frac{DCO}{2\bar{X}10^6}\right) - \left(\frac{DHC}{\bar{X}10^6}\right) + \frac{\alpha}{4}\left(1 - \frac{DHC}{\bar{X}10^6}\right) - \frac{0.75\alpha}{\left(\frac{K}{\frac{DCO}{\bar{X}10^6}}\right) + \left(\frac{1 - K}{1 - \frac{DHC}{\bar{X}10^6}}\right)}}$$

$$(f/a)_{stoich} = \frac{M_C + \alpha M_H}{138.18\left(1 + \frac{\alpha}{4}\right)}$$

$$\bar{X} = \frac{DCO_2}{10^2} + \frac{DCO}{10^6} + \frac{DHC}{10^6}$$

5.4 Multiply the dry nitric oxide volume concentration by the following humidity correction factor to obtain DKNO:

$$K_{NO_x} = \frac{1}{1 + A\,(G - 10.7) + B\,(T - 29.5)}$$

Where: $A = 0.308\ (f/a) - 0.0266$
$B = 0.209\ (f/a) + 0.00954$
T = temperature of inlet air, °C
G = g H_2O/kg dry air

$$K_{NO_x} = \frac{1}{1 + A\,(G - 75) + B\,(T - 85)}$$

Where: $A = 0.044\ (f/a) - 0.0038$
$B = 0.116\ (f/a) + 0.0053$
T = temperature of inlet air, °F
G = grains H_2O/lb of dry air

5.5 Calculate the mass emissions of each species in grams/hour for each mode as follows:

$$\text{HC g/h} = W_{HC} = \frac{(DHC/10^4)\ M_F}{(DCO/10^4) + DCO_2 + (DHC/10^4)}$$

$$\text{CO g/h} = W_{CO} = \frac{M_{CO}\ (DCO/10^4)\ M_F}{(M_C + \alpha\ M_H)\ [(DCO/10^4) + DCO_2 + (DHC/10^4)]}$$

$$NO_x\ \text{g/h} = W_{NO_x} = \frac{M_{NO_2}\ (DKNO_x/10^4)\ M_F}{(M_C + \alpha\ M_H)\ [(DCO/10^4) + DCO_2 + (DHC/10^4)]}$$

5.6 Weight the values of kW, W_{HC}, W_{CO}, W_{NO_x} as defined in 4.2.

5.7 Calculate the brake specific emissions for each test by summing the weighted values kW, W_{HC}, W_{CO}, and W_{NO_x} for each mode as follows:

$$BSHC = \frac{\Sigma \text{ weighted } W_{HC}}{\Sigma \text{ weighted kW}}$$

$$BSCO = \frac{\Sigma \text{ weighted } W_{CO}}{\Sigma \text{ weighted kW}}$$

$$BSNO_x = \frac{\Sigma \text{ weighted } W_{NO_x}}{\Sigma \text{ weighted kW}}$$

6. DATA VALIDATION:

It is a good practice to evaluate the data to detect leaks in the engine air intake system and gaseous emissions sampling system. This can be done in the following way which requires the measurement of both CO_2 and air flow during the test:

Compute the measured fuel: air ratio and dry CO_2. The point defined by those coordinates on the data validation curve shown in Fig. 1 should fall between the dashed lines. If the data falls outside the dashed lines, the test should be repeated.

7. APPENDICES:

Table A-1 shows some alternative weighting factors that have been proposed for European and off-highway use. Also shown for informational purposes is the Japanese heavy-duty diesel cycle.