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SURFACE VEHICLE RECOMMENDED PRACTICE

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DIESEL ENGINE EMISSION MEASUREMENT PROCEDURE

Foreword—This Reaffirmed Document has been changed only to reflect the new SAE Technical Standards Board Format.

1. *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 J177, J215, and J244 using nondispersive infrared equipment for CO and CO_2, a heated flame ionization analyzer for HC, and a high performance NDIR or a chemiluminescence analyzer for NO_x. 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. *References*

2.1 Applicable Publications

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

SAEJ177—Measurement of Carbon Dioxide, Carbon Monoxide, and Oxides of Nitrogen in Diesel Exhaust
SAE J215—Continuous Hydrocarbon Analysis of Diesel Emissions
SAE J244—Measurement of Intake Air or Exhaust Gas Flow of Diesel Engines
SAE J1349—Engine Power Test Code—Spark Ignition and Diesel

2.1.2 ASTM PUBLICATIONS—Available from ASTM, 100 Barr Harbor Dr., West Conshohocken, PA 19428-2959

ASTM D 86—Method for Distillation of Petroleum Products
ASTM D 93—Test Methods for Flash Point by Pensky-Martens Closed Tester
ASTM D 129—Test Method for Sulfur in Petroleum Products (General Bomb Method)

ASTM D 287—Test Method for API Gravity of Crude Petroleum and Petroleum Products (Hydrometer Method)
ASTM D 445—Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and the Calculation of Dynamic Viscosity)
ASTM D 613—Test Method for Ignition Quality of Diesel Fuels by the Octane Method
ASTM D 1319—Test Method for Hydrocarbon Types in Liquid Petroleum Products by Fluorescent Indicator Adsorption

3. Definitions

3.1 Diesel Engine—Any compression ignition engine.

3.2 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.

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

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

3.5 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.

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

3.7 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.

3.8 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.

3.9 Rated Torque—The maximum torque produced by an engine, as stated by the manufacturer.

3.10 Percent Load—The fraction of the maximum available torque at that engine speed.

4. Abbreviations—The abbreviations used in the document 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)
ϕ	= 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)
DHC = Hydrocarbon volume concentration in exhaust, PPM (dry)
$DKNO_x$ = NO volume concentration in exhaust, in PPM (dry and humidity corrected)
EIP = Absolute engine intake pressure, kPa (in Hg) = BARO-inlet restriction

$$f/a = \text{Dry fuel air ratio(measured)} = (f/a) \text{ wet } 1 + \frac{G}{1000} \qquad \text{(Eq. 1)}$$

G = Humidity of the inlet air in grams of water per kilogram of dry air
K = Water-gas equilibrium constant = 3.5
Kno_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)
$(M_c + \alpha M_H)$ = 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)
Mno_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 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_{NOx} = Mass rate of NO_x in exhaust, grams/h
Y = H_2O volume concentration in intake air

where:

$$Y = \frac{P_v}{BARO - P_v} \qquad \text{(Eq. 2)}$$

5. *Engine Dynamometer Test Procedure*

5.1 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.

5.2 Fuel Specification

5.2.1 The diesel fuels employed shall be clean and bright, with pour point and cloud point adequate for operability. The fuels may contain nonmetal additives as follows: Cetane improver, metal deactivator, antioxidant, dehazer, antirust, pour depressant, dye, and dispersant.

5.2.2 Fuel meeting the specifications in Table 1 is currently recommended in the U.S. Highway regulations. Other fuels may be used, realizing that some fuel properties affect exhaust emissions results.

TABLE 1—TEST FUEL SPECIFICATIONS

Item	ASTM Test No.	Range
Cetane number	D 613	42–50
Distillation range	D 86	
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	D 287	33–37
Total sulfur, %	D 129	0.2–0.5
Hydrocarbon composition	D 1319	
Aromatics, % min		27
Paraffins, naphthenes, olefins		Remainder
Flash point, °C (°F) min	D 93	54 (130)
Viscosity, m^2/s (cst)	D 445	$2–3.2 \times 10^{-6}$ (2–3.2)

5.3 Instrumentation

5.3.1 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)

5.3.2 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:

5.3.2.1 The determination of CO, CO_2, and NO_x concentrations shall be accomplished using sampling and analysis according to SAE J177.

5.3.2.2 The determination of HC concentration shall be accomplished using sampling and analysis by a heated flame ionization detector method using SAE J215.

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

5.4 Test Conditions

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

5.4.1.1 *Intake Air Temperature*—25 °C ± 5 °C (77 °F ± 9 °F)

5.4.1.2 *Barometric Pressure*—100 kPa ± 3 kPa (29.6 in Hg ± 1 in Hg)

5.4.1.3 *Fuel Temperature at Fuel Pump Inlet*—37 °C ± 5 °C (99 °F ± 9 °F)

5.4.1.4 *Intake Restriction*—The manufacturer's published maximum limit of air cleaner restriction.

5.4.1.5 *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.

5.5 Test Procedure for Exhaust Emissions

5.5.1 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.

5.5.2 PRETEST CONDITIONING PROCEDURE—Operate the engine until emission rates have stabilized.

5.5.3 EMISSIONS MEASUREMENT PROCEDURE

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

5.5.3.2 Operate the engine at the modes in Table 2.

5.5.3.3 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

TABLE 2—EMISSIONS TEST MODES

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

5.5.4 ANALYZER OUTPUT READING

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

5.5.4.2 Determine the concentration of HC, CO, CO_2, and NO_x in each mode from the analyzer output reading (5.5.4.1).

5.5.4.3 Convert dry concentrations to wet per SAE J177b.

6. Calculations—The test results for the emission test shall be derived through the following steps:

6.1 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. $NO_x = 0.0432 \times NOx_{CONC}$ (ppm) x exh. mass flow (lb/min)
$NO_{x\ mass} = 0.0952 \times NOx_{CONC}$ (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

6.2 Calculate the weighted average brake specific emissions for a cycle with the modal data from 6.1. 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 in Equations 3 to 8:

$$BSHC = \frac{\Sigma(HC_{mass} \times W_F)}{\Sigma(kW \times W_F)} \frac{g}{kW \cdot h} \quad \text{(Eq. 3)}$$

$$BSHC = \frac{\Sigma(HC_{mass} \times W_F)}{\Sigma(bhp \times W_F)} \frac{g}{bhp \cdot h} \quad \text{(Eq. 4)}$$

$$BSCO = \frac{\Sigma(CO_{mass} \times W_F)}{\Sigma(kW \times W_F)} \frac{g}{kW \cdot h} \quad \text{(Eq. 5)}$$

$$BSCO = \frac{\Sigma(CO_{mass} \times W_F)}{\Sigma(bhp \times W_F)} \frac{g}{bhp \cdot h} \quad \text{(Eq. 6)}$$

$$BSNO_x = \frac{\Sigma(NO_{x_{mass}} \times W_F)}{\Sigma(kW \times W_F)} \frac{g}{kW \cdot h} \quad \text{(Eq. 7)}$$

$$BSNO_x = \frac{\Sigma(NO_{x_{mass}} \times W_F)}{\Sigma(bhp \times W_F)} \frac{g}{bhp \cdot h} \quad \text{(Eq. 8)}$$

7. Alternate Calculations

7.1 Determine the exhaust species volume concentration for each mode.

7.2 Convert wet basis measurements to a dry basis by following:

Dry concentration = (K_W) x Wet concentration

K_W is defined as follows in Equation 9:

$$K_W = 1 + \left[\frac{\alpha\left(\frac{DCO_2}{10^2} + \frac{DCO}{10^6} + \frac{2y}{\phi}\right)\left(\frac{DCO}{10^2} + \frac{DCO}{10^6} + \frac{Whc}{10^6}\right)\left(1 + \frac{\alpha}{4}\right)}{2\left(1 + \frac{\frac{DCO}{10^6}}{\left(\frac{DCO_2}{10^2}\right)K}\right)} \right] \qquad \text{(Eq. 9)}$$

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

7.2.2 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.

7.3 Compute the dry (f/a) as follows in Equation 10:

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

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

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

7.4 Multiply the dry nitric oxide volume concentration by the following humidity correction factor to obtain $DKNO_x$ as shown in Equations 11 and 12:

$$K_{NO_x} = \frac{1}{1 + A(G - 10.7) + B(T - 29.5)} \qquad \text{(Eq. 11)}$$

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

$$K_{NO_x} = \frac{1}{1 + A(G - 75) + B(T - 85)} \quad \text{(Eq. 12)}$$

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

7.5 Calculate the mass emissions of each species in grams/hour for each mode as follows in Equations 13 to 15:

$$HCg/h = W_{HC} = \frac{(DHC/10^4)M_F}{(DCO/10^4) + DCO_2 + (DHC/10^4)} \quad \text{(Eq. 13)}$$

$$COg/h = W_{CO} = \frac{M_{CO}(DCO/10^4)M_F}{(M_C + \alpha M_H)[(DCO/10^4) + DCO_2 + (DHC/10^4)]} \quad \text{(Eq. 14)}$$

$$NO_Xg/h = W_{NO_x} = \frac{M_{NO_2}(DKNO_x/10^4)M_F}{(M_c + \alpha M_H)[(DCO/10^4) + DCO_2 + (DHC/10^4)]} \quad \text{(Eq. 15)}$$

7.6 Weight the values of kW, W_{HC}, W_{CO}, W_{NOx} as defined in 6.2.

7.7 Calculate the brake specific emissions for each test by summing the weighted values kW, W_{HC}, W_{CO}, W_{NOx} for each mode as follows in Equations 16 to 18:

$$BSHC = \frac{\Sigma \text{ weighted } W_{HC}}{\Sigma \text{ weighted kW}} \quad \text{(Eq. 16)}$$

$$BSCO = \frac{\Sigma \text{ weighted } W_{CO}}{\Sigma \text{ weighted kW}} \quad \text{(Eq. 17)}$$

$$BSNO_x = \frac{\Sigma \text{ weighted } W_{NO_x}}{\Sigma \text{ weighted kW}} \quad \text{(Eq. 18)}$$