

$$-\log_{10}(p_{\text{sat}}) = 9.09685 \cdot \left( \frac{273.16}{T_{\text{sat}}} - 1 \right) + 3.56654 \cdot \log_{10} \left( \frac{273.16}{T_{\text{sat}}} \right) + 0.87682 \cdot \left( \frac{T_{\text{sat}}}{273.16} - 1 \right) + 0.21386 \quad \text{Eq. 1065.645-2}$$

Example:

$$T_{\text{ice}} = -15.4 \text{ } ^\circ\text{C}$$

$$T_{\text{ice}} = -15.4 + 273.15 = 257.75 \text{ K}$$

$$-\log_{10}(p_{\text{sat}}) = 9.09685 \cdot \left( \frac{273.16}{257.75} - 1 \right) +$$

$$3.56654 \cdot \log_{10} \left( \frac{273.16}{257.75} \right) +$$

$$0.87682 \cdot \left( \frac{257.75}{273.16} - 1 \right) + 0.21386$$

$$-\log_{10}(p_{\text{H}_2\text{O}}) = -0.79821$$

$$p_{\text{H}_2\text{O}} = 10^{0.79821} = 0.15914 \text{ kPa}$$

(b) *Dewpoint.* If you measure humidity as a dewpoint, determine the amount of water in an ideal gas,  $x_{\text{H}_2\text{O}}$ , as follows:

$$x_{\text{H}_2\text{O}} = \frac{p_{\text{H}_2\text{O}}}{p_{\text{abs}}} \quad \text{Eq. 1065.645-3}$$

Where:

$x_{\text{H}_2\text{O}}$  = amount of water in an ideal gas.  
 $p_{\text{H}_2\text{O}}$  = water vapor pressure at the measured dewpoint,  $T_{\text{sat}} = T_{\text{dew}}$ .  
 $p_{\text{abs}}$  = wet static absolute pressure at the location of your dewpoint measurement.

Example:

$$p_{\text{abs}} = 99.980 \text{ kPa}$$

$$T_{\text{sat}} = T_{\text{dew}} = 9.5 \text{ } ^\circ\text{C}$$

Using Eq. 1065.645-2,

$$p_{\text{H}_2\text{O}} = 1.18489 \text{ kPa}$$

$$x_{\text{H}_2\text{O}} = 1.18489/99.980$$

$$x_{\text{H}_2\text{O}} = 0.011851 \text{ mol/mol}$$

(c) *Relative humidity.* If you measure humidity as a relative humidity, RH %, determine the amount of water in an ideal gas,  $x_{\text{H}_2\text{O}}$ , as follows:

$$x_{\text{H}_2\text{O}} = \frac{\text{RH}\% \cdot p_{\text{H}_2\text{O}}}{p_{\text{abs}}} \quad \text{Eq. 1065.645-4}$$

Where:

$x_{\text{H}_2\text{O}}$  = amount of water in an ideal gas.  
 RH % = relative humidity.  
 $p_{\text{H}_2\text{O}}$  = water vapor pressure at 100% relative humidity at the location of your relative humidity measurement,  $T_{\text{sat}} = T_{\text{amb}}$ .  
 $p_{\text{abs}}$  = wet static absolute pressure at the location of your relative humidity measurement.

Example:

$$\text{RH}\% = 50.77\%$$

$$p_{\text{abs}} = 99.980 \text{ kPa}$$

$$T_{\text{sat}} = T_{\text{amb}} = 20 \text{ } ^\circ\text{C}$$

Using Eq. 1065.645-2,

$$p_{\text{H}_2\text{O}} = 2.3371 \text{ kPa}$$

$$x_{\text{H}_2\text{O}} = (50.77\% \cdot 2.3371)/99.980$$

$$x_{\text{H}_2\text{O}} = 0.011868 \text{ mol/mol}$$

### § 1065.650 Emission calculations.

(a) *General.* Calculate brake-specific emissions over each test interval in a duty cycle. Refer to the standard-setting part for any calculations you might need to determine a composite result, such as a calculation that weights and sums the results of individual test intervals in a duty cycle. We specify three alternative ways to calculate brake-specific emissions, as follows:

(1) For any testing, you may calculate the total mass of emissions, as described in paragraph (b) of this section, and divide it by the total work generated over the test interval, as described in paragraph (c) of this section, using the following equation:

$$e = \frac{m}{W} \quad \text{Eq. 1065.650-1}$$

Example:

$$m_{\text{NO}_x} = 64.975 \text{ g}$$

$$W = 25.783 \text{ kW}\cdot\text{hr}$$

$$e_{\text{NO}_x} = 64.975/25.783$$

$$e_{\text{NO}_x} = 2.520 \text{ g/(kW}\cdot\text{hr)}$$

(2) For discrete-mode steady-state testing, you may calculate the ratio of emission mass rate to power, as described in paragraph (d) of this section, using the following equation:

$$e = \frac{\bar{m}}{P} \quad \text{Eq. 1065.650-2}$$

(3) For field testing, you may calculate the ratio of total mass to total work, where these individual values are determined as described in paragraph (e) of this section. You may also use this approach for laboratory testing, consistent with good engineering judgment. This is a special case in which you use a signal linearly proportional

§ 1065.650

40 CFR Ch. I (7-1-08 Edition)

to raw exhaust molar flow rate to determine a value proportional to total emissions. You then use the same linearly proportional signal to determine total work using a chemical balance of fuel, intake air, and exhaust as described in §1065.655, plus information about your engine's brake-specific fuel consumption. Under this method, flow meters need not meet accuracy specifications, but they must meet the applicable linearity and repeatability specifications in subpart D or subpart J of this part. The result is a brake-specific emission value calculated as follows:

$$e = \frac{\tilde{m}}{\tilde{W}} \quad \text{Eq. 1065.650-3}$$

Example:

$\tilde{m} = 805.5 \text{ - g}$   
 $\tilde{W} = 52.102 \text{ - kW}\cdot\text{hr}$   
 $e_{\text{CO}} = 805.5/52.102$   
 $e_{\text{CO}} = 2.520 \text{ g/(kW}\cdot\text{hr)}$

(b) *Total mass of emissions.* To calculate the total mass of an emission, multiply a concentration by its respective flow. For all systems, make preliminary calculations as described in paragraph (b)(1) of this section, then use the method in paragraphs (b)(2) through (4) of this section that is appropriate for your system. Calculate the total mass of emissions as follows:

(1) *Concentration corrections.* Perform the following sequence of preliminary calculations on recorded concentrations:

(i) Correct all concentrations measured on a "dry" basis to a "wet" basis, including dilution air background concentrations, as described in §1065.659.

(ii) Calculate all HC concentrations, including dilution air background concentrations, as described in §1065.660.

(iii) For emission testing with an oxygenated fuel, calculate any HC concentrations, including dilution air background concentrations, as described in §1065.665. See subpart I of this part for testing with oxygenated fuels.

(iv) Correct the total mass of NO<sub>x</sub> based on intake-air humidity as described in §1065.670.

(v) Calculate brake-specific emissions before and after correcting for drift, in-

cluding dilution air background concentrations, according to §1065.672.

(2) *Continuous sampling.* For continuous sampling, you must frequently record a continuously updated concentration signal. You may measure this concentration from a changing flow rate or a constant flow rate (including discrete-mode steady-state testing), as follows:

(i) *Varying flow rate.* If you continuously sample from a changing exhaust flow rate, synchronously multiply it by the flow rate of the flow from which you extracted it. We consider the following to be examples of changing flows that require a continuous multiplication of concentration times molar flow rate: Raw exhaust, exhaust diluted with a constant flow rate of dilution air, and CVS dilution with a CVS flow meter that does not have an upstream heat exchanger or electronic flow control. Account for dispersion and time alignment as described in §1065.201. This multiplication results in the flow rate of the emission itself. Integrate the emission flow rate over a test interval to determine the total emission. If the total emission is a molar quantity, convert this quantity to a mass by multiplying it by its molar mass, *M*. The result is the mass of the emission, *m*. Calculate *m* for continuous sampling with variable flow using the following equations:

$$m = M \cdot \sum_{i=1}^N x_i \cdot \dot{n}_i \cdot \Delta t \quad \text{Eq. 1065.650-4}$$

Example:

$M_{\text{NMHC}} = 13.875389 \text{ g/mol}$   
 $N = 1200$   
 $x_{\text{NMHC}1} = 84.5 \text{ } \mu\text{mol/mol} = 84.5 \cdot 10^{-6} \text{ mol/mol}$   
 $x_{\text{NMHC}2} = 86.0 \text{ } \mu\text{mol/mol} = 86.0 \cdot 10^{-6} \text{ mol/mol}$   
 $\dot{n}_{\text{exh}1} = 2.876 \text{ mol/s}$   
 $\dot{n}_{\text{exh}2} = 2.224 \text{ mol/s}$   
 $f_{\text{record}} = 1 \text{ Hz}$   
 Using Eq. 1065.650-5,  
 $\Delta t = 1/1 = 1 \text{ s}$   
 $m_{\text{NMHC}} = 13.875389 \cdot (84.5 \cdot 10^{-6} \cdot 2.876 + 86.0 \cdot 10^{-6} \cdot 2.224 + \dots + x_{\text{NMHC}1200} \cdot \dot{n}_{\text{exh}}) \cdot 1$   
 $m_{\text{NMHC}} = 25.23 \text{ g}$

(ii) *Constant flow rate.* If you continuously sample from a constant exhaust flow rate, calculate the mean concentration recorded over the test interval and treat the mean as a batch sample, as described in paragraph (b)(3)(ii)

of this section. We consider the following to be examples of constant exhaust flows: CVS diluted exhaust with a CVS flow meter that has either an upstream heat exchanger, electronic flow control, or both.

(3) *Batch sampling.* For batch sampling, the concentration is a single value from a proportionally extracted batch sample (such as a bag, filter, impinger, or cartridge). In this case, multiply the mean concentration of the batch sample by the total flow from which the sample was extracted. You may calculate total flow by integrating a changing flow rate or by determining the mean of a constant flow rate, as follows:

(i) *Varying flow rate.* If you collect a batch sample from a changing exhaust flow rate, extract a sample proportional to the changing exhaust flow rate. We consider the following to be examples of changing flows that require proportional sampling: Raw exhaust, exhaust diluted with a constant flow rate of dilution air, and CVS dilution with a CVS flow meter that does not have an upstream heat exchanger or electronic flow control. Integrate the flow rate over a test interval to determine the total flow from which you extracted the proportional sample. Multiply the mean concentration of the batch sample by the total flow from which the sample was extracted. If the total emission is a molar quantity, convert this quantity to a mass by multiplying it by its molar mass,  $M$ . The result is the mass of the emission,  $m$ . In the case of PM emissions, where the mean PM concentration is already in units of mass per mole of sample,  $\bar{M}_{PM}$ , simply multiply it by the total flow. The result is the total mass of PM,  $m_{PM}$ . Calculate  $m$  for batch sampling with variable flow using the following equation:

$$m = M \cdot \bar{x} \cdot \sum_{i=1}^N \dot{n}_i \cdot \Delta t \quad \text{Eq. 1065.650-6}$$

*Example:*

$$\begin{aligned} M_{NO_x} &= 46.0055 \text{ g/mol} \\ N &= 9000 \\ \bar{x}_{NO_x} &= 85.6 \text{ } \mu\text{mol/mol} = 85.6 \cdot 10^{-6} \text{ mol/mol} \\ \dot{n}_{dexh1} &= 25.534 \text{ mol/s} \\ \dot{n}_{dexh2} &= 26.950 \text{ mol/s} \\ f_{record} &= 5 \text{ Hz} \end{aligned}$$

Using Eq. 1065.650-5,

$$\begin{aligned} \Delta t &= 1/5 = 0.2 \\ m_{NO_x} &= 46.0055 \cdot 85.6 \cdot 10^{-6} \cdot (25.534 + 26.950 + \dots + \dot{n}_{dexh9000}) \cdot 0.2 \\ m_{NO_x} &= 4.201 \text{ g} \end{aligned}$$

(ii) *Constant flow rate.* If you batch sample from a constant exhaust flow rate, extract a sample at a constant flow rate. We consider the following to be examples of constant exhaust flows: CVS diluted exhaust with a CVS flow meter that has either an upstream heat exchanger, electronic flow control, or both. Determine the mean molar flow rate from which you extracted the constant flow rate sample. Multiply the mean concentration of the batch sample by the mean molar flow rate of the exhaust from which the sample was extracted, and multiply the result by the time of the test interval. If the total emission is a molar quantity, convert this quantity to a mass by multiplying it by its molar mass,  $M$ . The result is the mass of the emission,  $m$ . In the case of PM emissions, where the mean PM concentration is already in units of mass per mole of sample  $\bar{M}_{PM}$ , simply multiply it by the total flow, and the result is the total mass of PM,  $m_{PM}$ . Calculate  $m$  for sampling with constant flow using the following equations:

$$m = M \cdot \bar{x} \cdot \bar{n} \cdot \Delta t \quad \text{Eq. 1065.650-7}$$

and for PM or any other analysis of a batch sample that yields a mass per mole of sample,

$$\bar{M} = M \cdot \bar{x} \quad \text{Eq. 1065.650-8}$$

*Example:*

$$\begin{aligned} \bar{M}_{PM} &= 144.0 \text{ } \mu\text{g/mol} = 144.0 \cdot 10^{-6} \text{ g/mol} \\ \bar{n}_{dexh} &= 57.692 \text{ mol/s} \\ \Delta t &= 1200 \text{ s} \\ m_{PM} &= 144.0 \cdot 10^{-6} \cdot 57.692 \cdot 1200 \\ m_{PM} &= 9.9692 \text{ g} \end{aligned}$$

(4) *Additional provisions for diluted exhaust sampling; continuous or batch.* The following additional provisions apply for sampling emissions from diluted exhaust:

(i) For sampling with a constant dilution ratio ( $DR$ ) of air flow versus exhaust flow (e.g., secondary dilution for PM sampling), calculate  $m$  using the following equation:

$$m = m_{dil} \cdot (DR + 1) \quad \text{Eq. 1065.650-9}$$

*Example:*

§ 1065.650

40 CFR Ch. I (7-1-08 Edition)

$$m_{PMdil} = 6.853 \text{ g}$$

$$DR = 5:1$$

$$m_{PM} = 6.853 \cdot (5 + 1)$$

$$m_{PM} = 41.118 \text{ g}$$

(ii) For continuous or batch sampling, you may measure background emissions in the dilution air. You may then subtract the measured background emissions, as described in § 1065.667.

(c) *Total work.* To calculate total work, multiply the feedback engine speed by its respective feedback torque. Integrate the resulting value for power over a test interval. Calculate total work as follows:

$$W = \sum_{i=1}^N P_i \cdot \Delta t \quad \text{Eq. 1065.650-10}$$

$$P_i = f_{ni} \cdot T_i \quad \text{Eq. 1065.650-11}$$

*Example:*

$$N = 9000$$

$$f_{n1} = 1800.2 \text{ rev/min}$$

$$f_{n2} = 1805.8 \text{ rev/min}$$

$$T_1 = 177.23 \text{ N}\cdot\text{m}$$

$$T_2 = 175.00 \text{ N}\cdot\text{m}$$

$$C_{rev} = 2 \cdot \pi \text{ rad/rev}$$

$$C_{t1} = 60 \text{ s/min}$$

$$C_p = 1000 \text{ (N}\cdot\text{m)/kW}$$

$$f_{record} = 5 \text{ Hz}$$

$$C_{t2} = 3600 \text{ s/hr}$$

$$P_1 = \frac{1800.2 \cdot 177.23 \cdot 2 \cdot 3.14159}{60 \cdot 1000}$$

$$P_1 = 33.41 \text{ kW}$$

$$P_2 = 33.09 \text{ kW}$$

Using Eq. 1065.650-5,

$$\Delta t = 1/5 = 0.2 \text{ s}$$

$$W = \frac{(33.41 + 33.09 + \dots + P_{9000}) \cdot 0.2}{3600}$$

$$W = 16.875 \text{ kW}\cdot\text{hr}$$

(d) *Steady-state mass rate divided by power.* To determine steady-state brake-specific emissions for a test interval as described in paragraph (a)(2) of this section, calculate the mean steady-state mass rate of the emission,  $\bar{m}$ , and the mean steady-state power,  $\bar{P}$ , as follows:

(1) To calculate,  $\bar{m}$ , multiply its mean concentration,  $\bar{x}$ , by its corresponding mean molar flow rate,  $\bar{n}$ . If the result is

a molar flow rate, convert this quantity to a mass rate by multiplying it by its molar mass,  $M$ . The result is the mean mass rate of the emission,  $\dot{m}_{PM}$ . In the case of PM emissions, where the mean PM concentration is already in units of mass per mole of sample,  $M_{PM}$ , simply multiply it by the mean molar flow rate,  $\bar{n}$ . The result is the mass rate of PM,  $\dot{m}_{PM}$ . Calculate  $\bar{m}$  using the following equation:

$$\bar{m} = M \cdot \bar{x} \cdot \bar{n} \quad \text{Eq. 1065.650-12}$$

(2) Calculate  $\bar{P}$  using the following equation:

$$\bar{P} = \bar{f}_n \cdot \bar{T} \quad \text{Eq. 1065.650-13}$$

(3) *Ratio of mass and work.* Divide emission mass rate by power to calculate a brake-specific emission result as described in paragraph (a)(2) of this section.

(4) *Example.* The following example shows how to calculate mass of emissions using mean mass rate and mean power:

$$M_{CO} = 28.0101 \text{ g/mol}$$

$$\bar{x}_{CO} = 12.00 \text{ mmol/mol} = 0.01200 \text{ mol/mol}$$

$$\bar{n} = 1.530 \text{ mol/s}$$

$$\bar{f}_n = 3584.5 \text{ rev/min} = 375.37 \text{ rad/s}$$

$$\bar{T} = 121.50 \text{ N}\cdot\text{m}$$

$$\bar{m} = 28.0101 \cdot 0.01200 \cdot 1.530$$

$$\bar{m} = 0.514 \text{ g/s}$$

$$\bar{P} = 121.5 \cdot 375.37$$

$$\bar{P} = 45607 \text{ W} = 45.607 \text{ kW}$$

$$e_{CO} = 0.514/45.61$$

$$e_{CO} = 0.0113 \text{ g/(kW}\cdot\text{hr)}$$

(e) *Ratio of total mass of emissions to total work.* To determine brake-specific emissions for a test interval as described in paragraph (a)(3) of this section, calculate a value proportional to the total mass of each emission. Divide each proportional value by a value that is similarly proportional to total work.

(1) *Total mass.* To determine a value proportional to the total mass of an emission, determine total mass as described in paragraph (b) of this section, except substitute for the molar flow rate,  $\bar{n}$ , or the total flow,  $n$ , with a signal that is linearly proportional to molar flow rate,  $\bar{n}$ , or linearly proportional to total flow,  $\bar{n}$ , as follows:

$$\tilde{m}_{\text{fuel}i} = \frac{1}{w_{\text{fuel}}} \cdot \frac{M_C \cdot \tilde{n}_i \cdot X_{\text{Cproddry}i}}{1 + X_{\text{H}_2\text{O}i}} \quad \text{Eq. 1065.650-14}$$

(2) *Total work.* To calculate a value proportional to total work over a test interval, integrate a value that is proportional to power. Use information about the brake-specific fuel consumption of your engine,  $e_{\text{fuel}}$ , to convert a signal proportional to fuel flow rate to a signal proportional to power. To determine a signal proportional to fuel flow rate, divide a signal that is proportional to the mass rate of carbon products by the fraction of carbon in your fuel,  $w_c$ . For your fuel, you may use a measured  $w_c$  or you may use the default values in Table 1 of §1065.655. Calculate the mass rate of carbon from the amount of carbon and water in the exhaust, which you determine with a chemical balance of fuel, intake air, and exhaust as described in §1065.655. In the chemical balance, you must use concentrations from the flow that generated the signal proportional to molar flow rate,  $\tilde{n}$ , in paragraph (e)(1) of this section. Calculate a value proportional to total work as follows:

$$\tilde{W} = \sum_{i=1}^N \tilde{P}_i \cdot \Delta t \quad \text{Eq. 1065.650-15}$$

Where:

$$\tilde{P}_i = \frac{\tilde{m}_{\text{fuel}i}}{e_{\text{fuel}}} \quad \text{Eq. 1065.650-16}$$

(3) Divide the value proportional to total mass by the value proportional to total work to determine brake-specific emissions, as described in paragraph (a)(3) of this section.

(4) The following example shows how to calculate mass of emissions using proportional values:

$N = 3000$   
 $f_{\text{record}} = 5 \text{ Hz}$   
 $e_{\text{fuel}} = 285 \text{ g/(kW}\cdot\text{hr)}$   
 $w_{\text{fuel}} = 0.869 \text{ g/g}$   
 $M_C = 12.0107 \text{ g/mol}$   
 $\dot{n}_1 = 3.922 \text{ mol/s} = 14119.2 \text{ mol/hr}$   
 $X_{\text{Cproddry}1} = 91.634 \text{ mmol/mol} = 0.091634 \text{ mol/mol}$   
 $X_{\text{H}_2\text{O}1} = 27.21 \text{ mmol/mol} = 0.02721 \text{ mol/mol}$   
 Using 1065.650-5,  
 $\Delta t = 0.2 \text{ s}$

$$\tilde{W} = \frac{12.0107 \cdot \left[ \frac{3.922 \cdot 0.091634}{1 + 0.02721} + \frac{\tilde{n}_2 \cdot X_{\text{Cproddry}2}}{1 + X_{\text{H}_2\text{O}2}} + \dots + \frac{\tilde{n}_{3000} \cdot X_{\text{Cpdry}3000}}{1 + X_{\text{H}_2\text{O}n3000}} \right] \cdot 0.2}{285 \cdot 0.869}$$

$\tilde{W} = 5.09 \text{ ~ (kW}\cdot\text{hr)}$

(f) *Rounding.* Round emission values only after all calculations are complete and the result is in g/(kW·hr) or units equivalent to the units of the standard, such as g/(hp·hr). See the definition of "Round" in §1065.1001.

EFFECTIVE DATE NOTE: At 73 FR 37328, June 30, 2008., §1065.650 was revised, effective July 7, 2008. For the convenience of the user, the revised text is set forth as follows:

**§ 1065.650 Emission calculations.**

(a) *General.* Calculate brake-specific emissions over each test interval in a duty cycle. Refer to the standard-setting part for any

calculations you might need to determine a composite result, such as a calculation that weights and sums the results of individual test intervals in a duty cycle. For summations of continuous signals, each indexed value (i.e., "i") represents (or approximates) the mean value of the parameter for its respective time interval, delta-t.

(b) We specify three alternative ways to calculate brake-specific emissions, as follows:

(1) For any testing, you may calculate the total mass of emissions, as described in paragraph (c) of this section, and divide it by the total work generated over the test interval, as described in paragraph (d) of this section, using the following equation: