

TABLE 1 OF § 1065.202.—DATA RECORDING AND CONTROL MINIMUM FREQUENCIES

| Applicable section                       | Measured values   | Minimum frequency               |
|--|---|---------------------------------|
| § 1065.510 .....                         | Speed and torque during an engine step-map ....                                 | 1 mean value per step.          |
| § 1065.510 .....                         | Speed and torque during an engine sweep-map .....                               | 1 Hz averages of 5 Hz samp.     |
| § 1065.514, § 1065.530 .....             | Duty cycle reference and feedback speeds and torques for control and recording. | 5 Hz.                           |
| § 1065.520, § 1065.530, § 1065.550 ..... | Continuous concentrations of raw or dilute analyzers.                           | 1 Hz.                           |
| § 1065.520, § 1065.530, § 1065.550 ..... | Batch concentrations of raw or dilute analyzers ..                              | 1 mean value per test interval. |
| § 1065.530, § 1065.545 .....             | Diluted exhaust flow rate from a CVS with a heat exchanger.                     | 1 Hz.                           |
| § 1065.530, § 1065.545 .....             | Diluted exhaust flow rate from a CVS without a heat exchanger.                  | 5 Hz.                           |
| § 1065.530, § 1065.545 .....             | Intake-air, dilution-air, or raw-exhaust flow rate ...                          | 5 Hz.                           |
| § 1065.530, § 1065.545 .....             | Sample flow from a CVS that has a heat exchanger.                               | 1 Hz.                           |
| § 1065.530, § 1065.545 .....             | Sample flow from a CVS does not have a heat exchanger.                          | 5 Hz.                           |

**§ 1065.205 Performance specifications for measurement instruments.**

Your test system as a whole must meet all the applicable calibrations, performance checks, and test-validation criteria specified in subparts D and F of this part (and subpart J of this part for field testing). We recommend that you take the following steps to ensure that your test system performs adequately:

(a) Meet the specifications for individual measurement instruments in Table 1 of this section. For instruments with multiple ranges, this applies to all the ranges you use for testing. The accuracy specifications represent deviations from a true value or a calibration-standard value.

(b) Sample and record the quantity at the rate specified in Table 1 of this

section if your instrument meets the rise time and fall time in the table. Note that § 1065.308 requires that the product of the rise time and the frequency to be 5 or greater for continuous-analyzer systems.

(c) Keep any documentation from instrument manufacturers showing that instruments meet specifications.

TABLE 1 OF § 1065.205.—RECOMMENDED PERFORMANCE SPECIFICATIONS FOR MEASUREMENT INSTRUMENTS

| Measurement instrument  | Measured quantity symbol | Complete system rise time and fall time | Recording update frequency | Accuracy <sup>a</sup> | Repeatability <sup>a</sup> | Noise <sup>a</sup> |
|---|--------------------------|---|----------------------------|-----------------------|----------------------------|--------------------|
| Engine speed transducer .....                                     | f <sub>n</sub> .....     | 1 s ..                                  | 5 Hz                       | 2.0 % of pt. or ..... | 1.0 % of pt. ....          | 0.05 % of max      |
|   |                          |   |                            | 0.5 % of max. ....    | 0.25 % of max. ....        |                    |
| Engine torque transducer .....                                    | T .....                  | 1 s ..                                  | 5 Hz                       | 2.0 % of pt. or ..... | 1.0 % of pt. ....          | 0.05 % of max      |
|   |                          |   |                            | 1.0 % of max. ....    | 0.5 % of max. ....         |                    |
| General pressure transducer (not a part of another instrument).   | p .....                  | 5 s ..                                  | 1 Hz                       | 2.0 % of pt. or ..... | 1.0 % of pt. ....          | 0.1 % of max       |
|   |                          |   |                            | 1.0 % of max. ....    | 0.50 % of max. ....        |                    |
| Barometer .....   | P <sub>barom</sub> ..... | 50 s                                    | 0.1 Hz.                    | 50 Pa .....           | 25 Pa .....                | 5 Pa               |
| Temperature sensor for PM-stabilization and balance environments. | T .....                  | 50 s                                    | 0.1 Hz.                    | 0.25 °C .....         | 0.1 °C .....               | 0.02 °C            |
| Other temperature sensor (not a part of another instrument).      | T .....                  | 5 s ..                                  | 1 Hz                       | 2 °C .....            | 1 °C .....                 | 0.2 °C             |
| Dewpoint sensor for PM-stabilization and balance environments.    | T <sub>dew</sub> ..      | 50 s                                    | 0.1 Hz.                    | 0.25 °C .....         | 0.1 °C .....               | 0.02 °C            |
| Other dewpoint sensor .....                                       | T <sub>dew</sub> ..      | 50 s                                    | 0.1 Hz.                    | 1 °C .....            | 0.5 °C .....               | 0.1 °C             |
| Fuel flow meter (Fuel totalizer in parentheses).                  | m .....                  | 5 s ..                                  | 1 Hz                       | 2.0 % of pt. or ..... | 1.0 % of pt. ....          | 0.5 % of max.      |
|   |                          | (N/A)                                   | (N/A)                      | 1.5 % of max. ....    | 0.75 % of max. ....        |                    |
| Diluted exhaust meter .....                                       | n .....                  | 5 s ..                                  | 1 Hz                       | 2.0 % of pt. or ..... | 1.0 % of pt. ....          | 1.0 % of max       |
|   |                          |   |                            | 1.5 % of max. ....    | 0.75 % of max. ....        |                    |
| Dilution air, inlet air, exhaust, and sample flow meters.         | n .....                  | 1 s ..                                  | 5 Hz                       | 2.5 % of pt. or ..... | 1.25 % of pt. ....         | 1.0 % of max       |
|   |                          |   |                            | 1.5 % of max. ....    | 0.75 % of max. ....        |                    |
| Constituent concentration, continuous analyzer.                   | x .....                  | 5 s ..                                  | 1 Hz                       | 2.0 % of pt. ....     | 1.0 % of pt. ....          | 0.2 % of max       |
|   |                          |   |                            | 2.0 % of meas. ....   | 1.0 % of meas. ....        |                    |
| Constituent concentration, batch analyzer.                        | x .....                  | N/A                                     | N/A ..                     | 2.0 % of pt. ....     | 1.0 % of pt. ....          | 0.2 % of max       |
|   |                          |   |                            | 2.0 % of meas. ....   | 1.0 % of meas. ....        |                    |
| Gravimetric PM balance .....                                      | m <sub>PM</sub> .....    | N/A                                     | N/A ..                     | See § 1065.790 .....  | 0.25 µg .....              | 0.1 µg             |

TABLE 1 OF § 1065.205.—RECOMMENDED PERFORMANCE SPECIFICATIONS FOR MEASUREMENT INSTRUMENTS—  
Continued

| Measurement instrument    | Meas-<br>ured<br>quan-<br>tity<br>sym-<br>bol | Com-<br>plete<br>sys-<br>tem<br>rise<br>time<br>and<br>fall<br>time | Re-<br>cord-<br>ing<br>up-<br>date<br>fre-<br>quen-<br>cy | Accuracy <sup>a</sup>                    | Repeatability <sup>a</sup>               | Noise <sup>a</sup> |
|---------------------------|---|---|---|--|--|--------------------|
| Inertial PM balance ..... | m <sub>PM</sub>                               | 5 s ..  | 1 Hz  | 2.0 % of pt. ....<br>2.0 % of meas. .... | 1.0 % of pt. ....<br>1.0 % of meas. .... | 0.2 % of max.      |

<sup>a</sup> Accuracy, repeatability, and noise are determined with the same collected data, as described in § 1065.305. "pt." refers to a single point at the average value expected during testing at the standard—the reference value used in § 1065.305; "max." refers to the maximum value expected during testing at the standard over any test interval, not the maximum of the instrument's range; "meas" refers to the flow-weighted average measured value during any test interval.

**Measurement of Engine Parameters and Ambient Conditions**

**§ 1065.210 Speed and torque transducers.**

(a) *Application.* Use instruments as specified in this section to measure engine speed and torque during engine operation.

(b) *Component requirements.* We recommend that you use speed and torque transducers that meet the specifications in Table 1 of § 1065.205. Note that your overall systems for measuring engine speed and torque must meet the linearity checks in § 1065.307.

(c) *Speed.* Use a magnetic or optical shaft-position detector with a resolution of at least 6° arc, in combination with a frequency counter that rejects common-mode noise.

(d) *Torque.* You may use a variety of methods to determine engine torque. As needed, and based on good engineering judgment, compensate for torque induced by the inertia of accelerating and decelerating components connected to the flywheel, such as the drive shaft and dynamometer rotor. Use any of the following methods to determine engine torque:

(1) Measure torque by mounting a strain gage in-line between the engine and dynamometer.

(2) Measure torque by mounting a strain gage on a lever arm connected to the dynamometer housing.

(3) Calculate torque from internal dynamometer signals, such as armature current, as long as you calibrate this measurement as described in § 1065.310.

**§ 1065.215 Pressure transducers, temperature sensors, and dewpoint sensors.**

(a) *Application.* Use instruments as specified in this section to measure pressure, temperature, and dewpoint.

(b) *Component requirements.* We recommend that you use pressure

transducers and temperature and dewpoint sensors that meet the specifications in Table 1 of § 1065.205. Note that your overall systems for measuring pressure, temperature, and dewpoint must meet the calibration and performance checks in § 1065.315.

(c) *Temperature.* For PM-balance environments or other precision temperature measurements, we recommend thermistors. For other applications we recommend thermocouples that are not grounded to the thermocouple sheath. You may use other temperature sensors, such as resistive temperature detectors (RTDs).

(d) *Pressure.* Pressure transducers must control their internal temperature or compensate for temperature changes over their expected operating range. Transducer materials must be compatible with the fluid being measured. For barometric pressure or other precision pressure measurements, we recommend either capacitance-type or laser-interferometer transducers. For other applications, we recommend either strain gauge or capacitance-type pressure transducers. You may use other pressure-measurement instruments, such as manometers, where appropriate.

(e) *Dewpoint.* For PM-stabilization environments, we recommend chilled-surface hygrometers. For other applications, we recommend thin-film capacitance sensors. You may use other dewpoint sensors, such as a wet-bulb/dry-bulb psychrometer, where appropriate.

**Flow-Related Measurements**

**§ 1065.220 Fuel flow meter.**

(a) *Application.* You may use fuel flow in combination with a chemical balance of carbon (or oxygen) between the fuel, inlet air, and raw exhaust to calculate raw exhaust flow as described in § 1065.650, as follows:

(1) Use the actual value of calculated raw exhaust flow rate in the following cases:

(i) For multiplying raw exhaust flow rate with continuously sampled concentrations.

(ii) For multiplying total raw exhaust flow with batch-sampled concentrations.

(2) In the following cases, you may use a signal that does not give the actual value of raw exhaust, as long as it is linearly proportional to the exhaust flow rate's actual calculated value:

(i) For feedback control of a proportional sampling system, such as a partial-flow dilution system.

(ii) For multiplying with continuously sampled constituent concentrations, if the same signal is used in a chemical-balance calculation to determine work from brake-specific fuel consumption and fuel consumed.

(b) *Component requirements.* We recommend that you use a fuel flow meter that meets the specifications in Table 1 of § 1065.205. We recommend a fuel flow meter that measures mass directly, such as one that relies on gravimetric or inertial measurement principles. This may involve using a meter with one or more scales for weighing fuel or using a Coriolis meter. Note that your overall system for measuring fuel flow must meet the linearity check in § 1065.307 and the calibration and performance checks in § 1065.320.

(c) *Recirculating fuel.* In any fuel-flow measurement, account for any fuel that bypasses the engine or returns from the engine to the fuel storage tank.

(d) *Flow conditioning.* For any type of fuel flow meter, condition the flow if needed to prevent wakes, eddies, circulating flows, or flow pulsations from affecting the accuracy or repeatability of the meter. You may accomplish this by using a sufficient length of straight tubing (such as a

length equal to 10 pipe diameters) or by using specially designed tubing bends, orifice plates or straightening fins to establish a predictable velocity profile upstream of the meter.

#### § 1065.225 Intake-air flow meter.

(a) *Application.* You may use an intake-air flow meter in combination with a chemical balance of carbon (or oxygen) between the fuel, inlet air, and raw exhaust to calculate raw exhaust flow as described in § 1065.650, as follows:

(1) Use the actual value of calculated raw exhaust in the following cases:

(i) For multiplying raw exhaust flow rate with continuously sampled concentrations.

(ii) For multiplying total raw exhaust flow with batch-sampled concentrations.

(2) In the following cases, you may use a signal that does not give the actual value of raw exhaust, as long as it is linearly proportional to the exhaust flow rate's actual calculated value:

(i) For feedback control of a proportional sampling system, such as a partial-flow dilution system.

(ii) For multiplying with continuously sampled constituent concentrations, if the same signal is used in a chemical-balance calculation to determine work from brake-specific fuel consumption and fuel consumed.

(b) *Component requirements.* We recommend that you use an intake-air flow meter that meets the specifications in Table 1 of § 1065.205. This may include a laminar flow element, an ultrasonic flow meter, a subsonic venturi, a thermal-mass meter, an averaging Pitot tube, or a hot-wire anemometer. Note that your overall system for measuring intake-air flow must meet the linearity check in § 1065.307 and the calibration in § 1065.325.

(c) *Flow conditioning.* For any type of intake-air flow meter, condition the flow if needed to prevent wakes, eddies, circulating flows, or flow pulsations from affecting the accuracy or repeatability of the meter. You may accomplish this by using a sufficient length of straight tubing (such as a length equal to 10 pipe diameters) or by using specially designed tubing bends, orifice plates or straightening fins to establish a predictable velocity profile upstream of the meter.

#### § 1065.230 Raw exhaust flow meter.

(a) *Application.* You may use measured raw exhaust flow, as follows:

(1) Use the actual value of calculated raw exhaust in the following cases:

(i) Multiply raw exhaust flow rate with continuously sampled concentrations.

(ii) Multiply total raw exhaust with batch sampled concentrations.

(2) In the following cases, you may use a signal that does not give the actual value of raw exhaust, as long as it is linearly proportional to the exhaust flow rate's actual calculated value:

(i) For feedback control of a proportional sampling system, such as a partial-flow dilution system.

(ii) For multiplying with continuously sampled constituent concentrations, if the same signal is used in a chemical-balance calculation to determine work from brake-specific fuel consumption and fuel consumed.

(b) *Component requirements.* We recommend that you use a raw-exhaust flow meter that meets the specifications in Table 1 of § 1065.205. This may involve using an ultrasonic flow meter, a subsonic venturi, an averaging Pitot tube, a hot-wire anemometer, or other measurement principle. This would generally not involve a laminar flow element or a thermal-mass meter. Note that your overall system for measuring raw exhaust flow must meet the linearity check in § 1065.307 and the calibration and performance checks in § 1065.330.

(c) *Flow conditioning.* For any type of raw exhaust flow meter, condition the flow if needed to prevent wakes, eddies, circulating flows, or flow pulsations from affecting the accuracy or repeatability of the meter. You may accomplish this by using a sufficient length of straight tubing (such as a length equal to 10 pipe diameters) or by using specially designed tubing bends, orifice plates or straightening fins to establish a predictable velocity profile upstream of the meter.

(d) *Exhaust cooling.* You may cool raw exhaust upstream of a raw-exhaust flow meter, as long as you observe all the following provisions:

(1) Do not sample PM downstream of the cooling device.

(2) Do not sample NMHC downstream of the cooling device for compression-ignition engines, 2-stroke spark-ignition engines, and 4-stroke spark ignition engines below 19 kW if it causes exhaust temperatures above 202 °C to decrease to below 180 °C.

(3) Do not sample NO<sub>x</sub> downstream of the cooling device if it causes aqueous condensation.

(4) If cooling causes aqueous condensation before the flow reaches the raw-exhaust flow meter, measure dewpoint and pressure at the flow meter's inlet. Use this dewpoint for emission calculations in § 1065.650.

#### § 1065.240 Dilution air and diluted exhaust flow meters.

(a) *Application.* Use a diluted exhaust flow meter to determine instantaneous diluted exhaust flow rates or total diluted exhaust flow over a test interval. You may use the difference between a diluted exhaust flow meter and a dilution air meter to calculate raw exhaust flow rates or total raw exhaust flow over a test interval.

(b) *Component requirements.* We recommend that you use a diluted exhaust flow meter that meets the specifications in Table 1 of § 1065.205. Note that your overall system for measuring diluted exhaust flow must meet the linearity check in § 1065.307 and the calibration and performance checks in § 1065.340 and § 1065.341. You may use the following meters:

(1) For constant-volume sampling (CVS) of the total flow of diluted exhaust, you may use a critical-flow venturi (CFV), a positive-displacement pump (PDP), a subsonic venturi (SSV), or an ultrasonic flow meter (UFM). Combined with an upstream heat exchanger, either a CFV or a PDP will also function as a passive flow controller in a CVS system. However, you may also combine any flow meter with any active flow control system to maintain proportional sampling of exhaust constituents. You may control the total flow of diluted exhaust, or one or more sample flows, or a combination of these flow controls to maintain proportional sampling.

(2) For any other dilution system, you may use a laminar flow element, an ultrasonic flow meter, a subsonic venturi, critical-flow venturis, a positive-displacement meter, a thermal-mass meter, an averaging Pitot tube, or a hot-wire anemometer.

(c) *Flow conditioning.* For any type of diluted exhaust flow meter, condition the flow if needed to prevent wakes, eddies, circulating flows, or flow pulsations from affecting the accuracy or repeatability of the meter. For some meters, you may accomplish this by using a sufficient length of straight tubing (such as a length equal to 10 pipe diameters) or by using specially designed tubing bends, orifice plates or straightening fins to establish a predictable velocity profile upstream of the meter.

(d) *Exhaust cooling.* You may cool diluted exhaust upstream of a diluted exhaust flow meter. If cooling causes aqueous condensation before the flow reaches the meter, then measure the dewpoint and pressure at the flow meter's inlet. Use this dewpoint and pressure for emission calculations in § 1065.650.

**§ 1065.245 Sample flow meter for batch sampling.**

(a) *Application.* Use a sample flow meter to determine sample flow rates or total flow sampled into a batch sampling system over a test interval. You may use the difference between a diluted exhaust sample flow meter and a dilution air meter to calculate raw exhaust flow rates or total raw exhaust flow over a test interval.

(b) *Component requirements.* We recommend that you use a sample flow meter that meets the specifications in Table 1 of § 1065.205. This may involve a laminar flow element, an ultrasonic flow meter, a subsonic venturi, critical-flow venturis, a positive-displacement meter, a thermal-mass meter, an averaging Pitot tube, or a hot-wire anemometer. Note that your overall system for measuring sample flow must meet the linearity check in § 1065.307.

(c) *Flow conditioning.* For any type of sample flow meter, condition the flow if needed to prevent wakes, eddies, circulating flows, or flow pulsations from affecting the accuracy or repeatability of the meter. For some meters, you may accomplish this by using a sufficient length of straight tubing (such as a length equal to 10 pipe diameters) or by using specially designed tubing bends, orifice plates or straightening fins to establish a predictable velocity profile upstream of the meter.

**§ 1065.248 Gas divider.**

(a) *Application.* You may use a gas divider to blend calibration gases.

(b) *Component requirements.* Use a gas divider that blends gases to the specifications of § 1065.750 and to the flow-weighted concentrations expected during testing. You may use critical-flow gas dividers, capillary-tube gas dividers, or thermal-mass-meter gas dividers. Note that your overall gas-divider system must meet the linearity check in § 1065.307.

**CO and CO<sub>2</sub> Measurements****§ 1065.250 Nondispersive infra-red analyzer.**

(a) *Application.* Use a nondispersive infra-red (NDIR) analyzer to measure CO and CO<sub>2</sub> concentrations in raw or diluted exhaust for either batch or continuous sampling.

(b) *Component requirements.* We recommend that you use an NDIR analyzer that meets the specifications in Table 1 of § 1065.205. Note that your NDIR-based system must meet the calibration and performance checks in § 1065.350 and § 1065.355 and, for continuous measurement, it must also meet the linearity check in § 1065.307.

**Hydrocarbon Measurements****§ 1065.260 Flame ionization detector.**

(a) *Application.* Use a flame ionization detector (FID) analyzer to measure hydrocarbon concentrations in raw or diluted exhaust for either batch or continuous sampling. Determine hydrocarbon concentrations on a carbon number basis of one (1), C<sub>1</sub>. Determine methane and nonmethane hydrocarbon values as described in paragraph (e) of this section. See subpart I of this part for special provisions that apply to measuring hydrocarbons when testing with oxygenated fuels.

(b) *Component requirements.* We recommend that you use a FID analyzer that meets the specifications in Table 1 of § 1065.205. Note that your FID-based system for measuring THC must meet all of the performance checks for hydrocarbon measurement in subpart D of this part.

(c) *Heated FID analyzers.* For diesel-fueled engines, two-stroke spark-ignition engines, and four-stroke spark-ignition engines below 19 kW, you must use heated FID analyzers that maintain all surfaces that are exposed to emissions at a temperature of  $(191 \pm 11) ^\circ\text{C}$ .

(d) *FID fuel and burner air.* Use FID fuel and burner air that meet the specifications of § 1065.750. Do not allow the FID fuel and burner air to mix before entering the FID analyzer to ensure that the FID analyzer operates with a diffusion flame and not a premixed flame.

(e) *Methane.* FID analyzers measure total hydrocarbons (THC). To determine nonmethane hydrocarbons (NMHC), quantify methane, CH<sub>4</sub>, either with a nonmethane cutter and a FID analyzer as described in § 1065.265, or with a gas chromatograph as described in § 1065.267. Instead of measuring methane, you may consider that 2% of measured total hydrocarbons is methane, as described in § 1065.660. For a FID analyzer used to determine NMHC, determine its response factor to CH<sub>4</sub>, RF<sub>CH<sub>4</sub></sub>, as described in § 1065.360. Note that NMHC-related calculations are described in § 1065.660.

**§ 1065.265 Nonmethane cutter.**

(a) *Application.* You may use a nonmethane cutter to measure CH<sub>4</sub> with a FID analyzer. A nonmethane cutter oxidizes all nonmethane hydrocarbons to CO<sub>2</sub> and H<sub>2</sub>O. Instead of measuring methane, you may consider that 2% of measured total hydrocarbons is methane, as described in § 1065.660. You may use a nonmethane cutter for raw or diluted exhaust for batch or continuous sampling.

(b) *System performance.* Determine nonmethane-cutter performance as described in § 1065.365 and use the results to calculate NMHC emission in § 1065.660.

(c) *Configuration.* Configure the nonmethane cutter with a bypass line for the performance check described in § 1065.365.

(d) *Optimization.* You may optimize a nonmethane cutter to maximize the penetration of CH<sub>4</sub> and the oxidation of all other hydrocarbons. You may dilute a sample with purified air or oxygen (O<sub>2</sub>) upstream of the nonmethane cutter to optimize its performance. You must account for any sample dilution in emission calculations.

**§ 1065.267 Gas chromatograph.**

(a) *Application.* You may use a gas chromatograph to measure CH<sub>4</sub> concentrations of diluted exhaust for batch sampling. Instead of measuring methane, you may consider that 2% of measured total hydrocarbons is methane, as described in § 1065.660. While you may also use a nonmethane cutter to measure CH<sub>4</sub>, as described in § 1065.265, use a reference procedure based on a gas chromatograph for comparison with any proposed alternate measurement procedure under § 1065.10.

(b) *Component requirements.* We recommend that you use a gas chromatograph that meets the specifications in Table 1 of § 1065.205.

**NO<sub>x</sub> Measurements****§ 1065.270 Chemiluminescent detector.**

(a) *Application.* You may use a chemiluminescent detector (CLD) to measure NO<sub>x</sub> concentration in raw or diluted exhaust for batch or continuous sampling. We generally accept a CLD for NO<sub>x</sub> measurement, even though it measures only NO (and NO<sub>2</sub>, when coupled with an NO<sub>2</sub>-to-NO converter), since conventional engines and aftertreatment systems do not emit significant amounts of NO<sub>x</sub> species other than NO and NO<sub>2</sub>. Use good engineering judgment to measure other NO<sub>x</sub> species, as appropriate. While you may also use other instruments to measure NO<sub>x</sub>, as described in § 1065.272 and § 1065.275, use a reference procedure based on a chemiluminescent detector for comparison with any proposed alternate measurement procedure under § 1065.10.

(b) *Component requirements.* We recommend that you use a CLD that meets the specifications in Table 1 of § 1065.205. Note that your CLD-based system must meet the quench check in § 1065.370 and, for continuous

measurements, it must also meet the linearity check in § 1065.307.

(c) *NO<sub>2</sub>-to-NO converter.* Place upstream of the CLD an internal or external NO<sub>2</sub>-to-NO converter that meets the performance check in § 1065.378. Configure the converter with a bypass to facilitate this performance check.

(d) *Humidity effects.* You must generally maintain CLD temperature to prevent aqueous condensation; however, you may disregard condensation control if you use one of the following configurations:

(1) The CLD is downstream of an NO<sub>2</sub>-to-NO converter that meets the performance check in § 1065.378.

(2) The CLD is downstream of a thermal chiller that meets the performance check in § 1065.376.

(e) *Response time.* You may use a heated CLD to improve CLD response time.

#### § 1065.272 Nondispersive ultraviolet analyzer.

(a) *Application.* You may use a nondispersive ultraviolet (NDUV) analyzer to measure NO<sub>x</sub> concentration in raw or diluted exhaust for batch or continuous sampling. We generally accept an NDUV for NO<sub>x</sub> measurement, even though it measures only NO and NO<sub>2</sub>, since conventional engines and aftertreatment systems do not emit significant amounts of other NO<sub>x</sub> species. Use good engineering judgment to measure other NO<sub>x</sub> species, as appropriate.

(b) *Component requirements.* We recommend that you use an NDUV analyzer that meets the specifications in Table 1 of § 1065.205. Note that your NDUV-based system must meet the performance checks in § 1065.372 and, for continuous measurement, it must also meet the linearity check in § 1065.307.

(c) *NO<sub>2</sub>-to-NO converter.* If your NDUV analyzer measures only NO, place upstream of the NDUV analyzer an internal or external NO<sub>2</sub>-to-NO converter that meets the performance check in § 1065.378. Configure the converter with a bypass to facilitate this performance check.

(d) *Humidity effects.* You must generally maintain NDUV temperature to prevent aqueous condensation; however, you may disregard condensation control if you use one of the following configurations:

(1) The NDUV is downstream of an NO<sub>2</sub>-to-NO converter that meets the performance check in § 1065.378.

(2) The NDUV is downstream of a thermal chiller that meets the performance check in § 1065.376.

#### § 1065.274 Zirconia (ZrO<sub>2</sub>) analyzer.

(a) *Application.* You may use a zirconia (ZrO<sub>2</sub>) analyzer to measure NO<sub>x</sub> concentration in raw exhaust for continuous sampling, as long as you stay within the analyzer manufacturer's specified limits with respect to acceptable O<sub>2</sub> exhaust concentrations and exhaust temperature. We generally accept a ZrO<sub>2</sub> analyzer for NO<sub>x</sub> measurement, even though it measures only NO and NO<sub>2</sub>, since conventional engines and aftertreatment systems do not emit significant amounts of other NO<sub>x</sub> species. Use good engineering judgment to measure other NO<sub>x</sub> species, as appropriate.

(b) *Component requirements.* We recommend that you use a ZrO<sub>2</sub> analyzer that meets the specifications in Table 1 of § 1065.205. Note that your ZrO<sub>2</sub>-based system must meet the performance checks in § 1065.374 and the linearity check in § 1065.307.

(c) *NO<sub>2</sub>-to-NO converter.* If your ZrO<sub>2</sub> analyzer measures only NO, place upstream of the ZrO<sub>2</sub> analyzer an NO<sub>2</sub>-to-NO converter that meets the performance check in § 1065.378. Configure the converter with a bypass to facilitate this performance check.

(d) *Humidity effects.* You must generally maintain ZrO<sub>2</sub> analyzer temperature to prevent aqueous condensation; however, you may disregard condensation control if you use one of the following configurations:

(1) The ZrO<sub>2</sub> analyzer is downstream of an NO<sub>2</sub>-to-NO converter that meets the performance check in § 1065.378.

(2) The ZrO<sub>2</sub> analyzer is downstream of a thermal chiller that meets the performance check in § 1065.376.

### O<sub>2</sub> MEASUREMENTS

#### § 1065.280 Paramagnetic detection analyzer.

(a) *Application.* You may use a paramagnetic detection (PMD) analyzer to measure O<sub>2</sub> concentration in raw or diluted exhaust for batch or continuous sampling. While you may also use a zirconia analyzer to measure O<sub>2</sub>, as described in § 1065.283, use a reference procedure based on paramagnetic detection analyzers for comparison with any proposed alternate measurement procedures under § 1065.10

(b) *Component requirements.* We recommend that you use a PMD analyzer that meets the specifications in Table 1 of § 1065.205. Note that it must meet the linearity check in § 1065.307 for continuous measurements.

(c) *Interference gas compensation.* Compensate for PMD interference gases according to ISO 8178-1, Section 8.9.4 (incorporated by reference in § 1065.1010).

#### § 1065.284 Zirconia (ZrO<sub>2</sub>) analyzer.

(a) *Application.* You may use a zirconia (ZrO<sub>2</sub>) analyzer to measure O<sub>2</sub> concentration in raw exhaust for continuous sampling.

(b) *Component requirements.* We recommend that you use a ZrO<sub>2</sub> analyzer that meets the specifications in Table 1 of § 1065.205. Note that your ZrO<sub>2</sub>-based system must meet the linearity check in § 1065.307.

### PM MEASUREMENTS

#### § 1065.290 PM gravimetric balance.

(a) *Application.* Use a balance to weigh net PM on a sample medium for laboratory testing.

(b) *Component requirements.* We recommend that you use a balance that meets the specifications in Table 1 of § 1065.205. Note that your balance-based system must meet the linearity check in § 1065.307. If the balance uses internal calibration weights for routine spanning and linearity checks, the calibration weights must meet the specifications in § 1065.790. While you may also use an inertial balance to measure PM, as described in § 1065.295, use a reference procedure based on a gravimetric balance for comparison with any proposed alternate measurement procedure under § 1065.10.

(c) *Periodic verification.* Get the balance manufacturer or a representative approved by the balance manufacturer to verify the balance performance at least once every 12 months.

(d) *Pan design.* Use a balance pan designed to minimize corner loading of the balance, as follows:

(1) Use a pan that centers the PM sample on the weighing pan. For example, use a pan in the shape of a cross that has upswep tips that center the PM sample media on the pan.

(2) Use a pan that positions the PM sample as low as possible.

(e) *Balance configuration.* Configure the balance for optimum settling time and stability at your location.

#### § 1065.295 PM inertial balance for field-testing analysis.

(a) *Application.* You may use an inertial balance to quantify net PM on a sample medium for field testing.

(b) *Component requirements.* We recommend that you use a balance that meets the specifications in Table 1 of § 1065.205. Note that your balance-based system must meet the linearity check in § 1065.307. If the balance uses an internal calibration process for routine spanning and linearity checks, the process must be NIST-traceable.

(c) *Periodic verification.* Get the balance manufacturer or a

representative approved by the balance manufacturer to verify the balance performance at least once every 12 months.

**Subpart D—Calibrations and Performance Checks**

**§ 1065.301 Overview and general provisions.**

(a) This subpart describes required and recommended calibrations and performance checks for measurement instruments. See subpart C of this part for specifications and system requirements that apply to individual instruments.

(b) You must generally use complete measurement systems when performing

calibrations or performance checks. For example, this would generally involve evaluating instruments based on values recorded with the complete system you use for recording test data, including analog-to-digital converters. For some calibrations and performance checks, we may specify that you disconnect part of the measurement system to introduce a simulated signal.

(c) If we do not specify a calibration or performance check for a portion of your measurement system, calibrate that portion of your system and check its performance at a frequency consistent with any recommendations from the measurement-system manufacturer,

consistent with good engineering judgment.

(d) Use NIST-traceable standards to the tolerances we specify for calibrations and performance checks. Where we specify the need to use NIST-traceable standards, you may alternatively ask for our approval to use international standards that are not traceable to NIST standards.

**§ 1065.303 Summary of required calibration and performance checks**

(a) The following table summarizes the required and recommended calibrations and performance checks described in this subpart. The table also indicates when these have to be performed.

TABLE 1 OF § 1065.303—SUMMARY OF REQUIRED CALIBRATION AND PERFORMANCE CHECKS

| Calibration or performance check   | Perform calibration or performance check   |
|--|--|
| § 1065.305: accuracy, repeatedly and noise .....   | <i>Accuracy:</i> not required, but recommend for initial installation.<br><i>Repeatability:</i> not required, but recommend for initial installation.<br><i>Noise:</i> required during initial installation only if you correct for noise (See § 1065.658).  |
| § 1065.307: Linearity .....  | <i>Speed:</i> Initial installation, and after major maintenance.<br><i>Torque:</i> Once every 12 months, and after major maintenance.<br><i>Flows:</i> Once every 12 months, and after major maintenance unless flow is verified by propane check or carbon (or oxygen) balance.<br><i>Continuous analyzers:</i> Once every 6 months, and after major maintenance. |
| § 1065.308: continuous analyzer system response .....  | Initial installation and after major system reconfiguration.   |
| § 1065.310: torque .....   | Initial installation and good engineering judgment afterward.  |
| § 1065.315: pressure, temperature, dewpoint .....  | Initial installation and good engineering judgment afterward.  |
| § 1065.320: fuel flow .....  | Initial installation and good engineering judgment afterward.  |
| § 1065.325: intake flow .....  | Initial installation and good engineering judgment afterward.  |
| § 1065.330: exhaust flow .....   | Initial installation and good engineering judgment afterward.  |
| § 1065.340: diluted exhaust flow (CVS) .....   | Initial installation, after major system reconfiguration, and as part of corrective action.  |
| § 1065.341: CVS and batch sampler verification .....   | After CVS and batch sampler calibration and in lieu of linearity check.  |
| § 1065.345: vacuum leak .....  | Initial installation, within 7 days of an emission test, and after major maintenance.  |
| § 1065.350: CO <sub>2</sub> NDIR H <sub>2</sub> O interference .....                         | Initial installation and after major maintenance.  |
| § 1065.355: CO NDIR CO <sub>2</sub> and H <sub>2</sub> O interference .....                  | Initial installation and after major maintenance.  |
| § 1065.360: FID optimization, etc .....  | <i>Calibrate, optimize, and determine CH<sub>4</sub> response:</i> initial installation and good engineering judgment afterward.<br><i>Check CH<sub>4</sub> response:</i> once every 12 months, and after major maintenance.   |
| § 1065.362: Raw exhaust FID O <sub>2</sub> interference .....                                | Initial installation and after major maintenance.  |
| § 1065.365: Nonmethane cutter penetration .....  | Once every 6 months, and after major maintenance.  |
| § 1065.370: CLD CO <sub>2</sub> and H <sub>2</sub> O quench .....                            | Initial installation and after major maintenance.  |
| § 1065.372: NDUV NMHC and H <sub>2</sub> O interference .....                                | Initial installation and after major maintenance.  |
| § 1065.374: ZrO <sub>2</sub> NH <sub>3</sub> interference and NO <sub>2</sub> response ..... | Initial installation and after major maintenance.  |
| § 1065.376: Chiller NO <sub>2</sub> penetration .....  | Initial installation and after major maintenance.  |
| § 1065.378: NO <sub>2</sub> to NO converter conversion .....                                 | Once every 6 months, and after major maintenance.  |
| § 1065.390: PM balance and weighing .....  | Within 12 hours of weighing, and after major balance and maintenance.  |

**§ 1065.305 Performance checks for accuracy, repeatability, and noise.**

(a) This section describes how to determine the accuracy, repeatability, and noise of an instrument. Table 1 of § 1065.205 specifies recommended values for individual instruments.

(b) We do not require you to check instrument accuracy or repeatability, and we require you to check instrument noise only as specified in paragraph (c) of this section. However, it may be useful to consider these performance checks to define a specification for a new instrument, to verify the

performance of a new instrument upon delivery, or to troubleshoot an existing instrument.

(c) If you correct a constituent analyzer for noise as described in § 65.658, you must have performed the noise performance check in this section within the past 12 months.

(d) In this section we use the letter “y” to denote a generic measured quantity, the superscript over-bar to denote an arithmetic mean (*i.e.*,  $\bar{y}$ ), and the subscript “<sub>ref</sub>” to denote the reference quantity being measured.

(e) Conduct these checks as follows:

(1) Prepare an instrument so it operates at its specified temperatures, pressures, and flows. Perform any instrument linearization or calibration procedures prescribed by the instrument manufacturer.

(2) Zero the instrument by introducing a zero signal. Depending on the instrument, this may be a zero-concentration gas, a reference signal, a set of reference thermodynamic conditions, or some combination of these. For gaseous constituent analyzers,

use a zero gas that meets the specifications of § 1065.750(a).

(3) Span the instrument by introducing a span signal. Depending on the instrument, this may be a span-concentration gas, a reference signal, a set of reference thermodynamic conditions, or some combination of these. For gaseous-exhaust constituent analyzers, use a span gas that meets the specifications of § 1065.750(a).

(4) Use the instrument to quantify a NIST-traceable reference quantity,  $y_{\text{ref}}$ . Select a reference quantity near the mean value expected during testing. For all exhaust constituent analyzers, use a quantity near the flow-weighted average concentration expected at the standard and known within the specifications of § 1065.750(a). For a noise performance check, use the same zero gas from paragraph (e) of this section as the reference quantity. In all cases, allow time for the instrument to stabilize while it measures the reference quantity. Stabilization time may include time to purge an instrument and time to account for its response.

(5) Sample 25 values, record the arithmetic mean of the 25 values  $\bar{y}_i$ , and record the standard deviation  $\sigma_i$ , of the 25 values. Refer to § 1065.602 for an example of calculating arithmetic mean and standard deviation.

(6) Subtract the reference value,  $y_{\text{ref}}$ , from the arithmetic mean,  $\bar{y}_i$ . Record this value as the error,  $\epsilon_i$ .

(7) Repeat the steps specified in paragraphs (e)(2) through (6) of this section until you have ten arithmetic means, ( $\bar{y}_1, \bar{y}_2, \bar{y}_3, \dots, \bar{y}_{10}$ ), ten standard deviations, ( $\sigma_1, \sigma_2, \sigma_3, \dots, \sigma_{10}$ ), and ten errors ( $\epsilon_1, \epsilon_2, \epsilon_3, \dots, \epsilon_{10}$ ).

(8) Instrument accuracy is the absolute difference between the reference quantity,  $y_{\text{ref}}$  and the arithmetic mean of the ten  $y_i$ . Refer to the accuracy example calculation in § 1065.602. We recommend that instrument accuracy be within the specifications in Table 1 of § 1065.205.

(9) Repeatability is two times the standard deviation of the ten errors: (e.g.  $\text{repeatability} = 2 \cdot \sigma_\epsilon$ ). Refer to the standard deviation example calculation in § 1065.602. We recommend that instrument repeatability be within the specifications in Table 1 of § 1065.205.

(10) Noise is two times the root mean square of the ten standard deviations, (e.g.  $\text{noise} = 2 \cdot \text{rms}_\sigma$ ). Refer to the root mean square example calculation in § 1065.602. We recommend that instrument noise be within the specifications in Table 1 of § 1065.205. Use this value in the noise correction specified in § 1065.657.

(11) You may use a measurement instrument that does not meet the

accuracy, repeatability, or noise specifications in Table 1 of § 1065.205, as long as you meet all the following criteria:

- (i) You try to correct the problem.
- (ii) Your measurement systems meet all required calibration, performance checks, and validation specifications.
- (iii) The measurement deficiency does not affect your ability to show that your engines comply with all applicable emission standards.

#### § 1065.307 Linearity check.

(a) Perform a linearity check on each measurement system listed in Table 1 of this section at least as frequently as indicated in the table, or more frequently, consistent with good engineering judgment; for example, if the measurement system manufacturer recommends it. Note that this linearity check replaces requirements that we previously referred to as calibration specifications.

(b) If a measurement system does not meet the applicable linearity criteria, correct the deficiency by re-calibrating, servicing, or replacing components as needed. Before you may use a measurement system that does not meet linearity criteria, you must get us to approve it under § 1065.10.

(c) The intent of a linearity check is to determine that a measurement system responds proportionally over the measurement range of interest. A linearity check generally consists of introducing a series of at least 10 reference values to a measurement system. These reference values are about evenly spaced from the lowest to the highest values expected during emission testing. The measurement system quantifies each reference value. The measured values are then collectively compared to the reference values by using the linearity criteria specified in Table 1 of this section.

(d) Use the following linearity-check protocol, or use good engineering judgment to develop a different protocol that satisfies the intent of this section, as described in paragraph (c) of this section:

(1) In this paragraph (d), we use the letter "y" to denote a generic measured quantity, the superscript over-bar to denote an arithmetic mean (i.e.,  $\bar{y}$ ), and the subscript "ref" to denote the known (or reference) quantity being measured.

(2) Operate a measurement system at its specified temperatures, pressures, and flows. This may include any specified adjustment or periodic calibration of the measurement system.

(3) Zero the instrument by introducing a zero signal. Depending on the instrument, this may be a zero-

concentration gas, a reference signal, a set of reference thermodynamic conditions, or some combination of these. For gaseous constituent analyzers, use a zero gas that meets the specifications of § 1065.750(a).

(4) Span the instrument by introducing a span signal. Depending on the instrument, this may be a span-concentration gas, a reference signal, a set of reference thermodynamic conditions, or some combination of these. For gaseous-exhaust constituent analyzers, use a span gas that meets the specifications of § 1065.750(a).

(5) Select 10 reference values,  $y_{\text{ref}i}$  that are nominally evenly spaced from the lowest to the highest values expected during emission testing. Generate reference quantities as described in paragraph (e) of this section. For gaseous-exhaust constituent analyzers, use gas concentrations known to be within the specifications of § 1065.750(a).

(6) Select the greatest reference value and introduce it to the measurement system.

(7) Allow time for the instrument to stabilize while it measures the reference value. Stabilization time may include time to purge an instrument and time to account for its response.

(8) At a frequency of f Hz specified in Table 1 of § 1065.205, measure the reference value 25 times and record the arithmetic mean of the 25 values,  $\bar{y}_i$ . Refer to § 1065.602 for an example of calculating an arithmetic mean.

(9) Select smallest reference value, and repeat steps in paragraphs (d)(7) and (d)(8) of this section.

(10) Alternate between selecting the highest and lowest remaining untested reference values until you have measured all the reference values.

(11) Use the arithmetic means,  $\bar{y}_i$ , and reference values,  $y_{\text{ref}i}$ , to calculate statistical values to compare to the criteria specified in Table 1 of this section. Use the statistical calculations as described in § 1065.602.

(e) This paragraph (e) describes recommended methods for generating reference values for the linearity-check protocol in paragraph (d) of this section. Use reference values that simulate actual values, or introduce an actual value and measure it with a reference-measurement system. In the latter case, the reference value is the value reported by the reference-measurement system. Reference values and reference-measurement systems must be traceable to NIST standards. Use the following recommended methods to generate reference values or use good engineering judgment to select a different method:

(1) *Engine speed.* Run the engine or dynamometer at a series of steady-state speeds and use a strobe, a photo tachometer, or a laser tachometer to record reference speeds.

(2) *Engine torque.* Use a series of calibration weights and a calibration lever arm to simulate engine torque. Alternately, you may use the engine or dynamometer itself to generate a nominal torque that is measured by a reference load cell in series with the torque measurement system. In this case use the reference load cell measurement as the reference value. Refer to § 1065.310 for a torque-calibration procedure similar to the linearity check in this section.

(3) *Fuel rate.* Operate the engine at a series of constant fuel-flow rates. Use a gravimetric reference measurement (such as a scale, balance, or mass comparator) at the inlet to the fuel-measurement system. Use a stopwatch to measure the time intervals over which reference masses of fuel are introduced to the fuel measurement system. The reference fuel mass divided

by the time interval is the reference fuel flow rate.

(4) *Flow rates—inlet air, dilution air, diluted exhaust, raw exhaust, or sample flow.* Use a reference flow meter with a blower or pump to simulate flow rates. Use a restrictor or diverter valve or a variable speed blower or pump to control the range of flow rates. Use the reference meter's response as the reference values. Because the flow range requirements for these various flows are large, we allow a variety of reference meters. For example, for diluted exhaust flow for a full flow dilution system we recommend a reference subsonic venturi flow meter with a restrictor valve and a blower to simulate flow rates. For inlet air, dilution air, diluted exhaust for partial flow dilution, raw exhaust or sample flow we allow reference meters such as critical flow orifices, critical flow venturis, laminar flow elements, master mass flow standards, or Roots meters. Ensure that your reference meter is calibrated by the flow meter manufacturer and that its calibration is traceable to NIST. If you use the difference of two flow measurements to

determine a single flow rate, you may use one of the measurements as a reference for the other.

(5) *Gas division.* At the outlet of the gas division system, connect a gas analyzer that meets the linearity check described in this section. Operate this analyzer consistent with how you would operate it for emission testing. Connect to the gas divider inlet a span gas for the analyzer. Use the gas division system to divide the span gas with purified air or nitrogen. Select gas divisions that you typically use. Use a selected gas division as the measured value. Use the quotient of the analyzer response divided by the span gas concentration as the reference value.

(6) *Continuous constituent concentration.* For reference values, use a series of gas cylinders of known gas concentration or use a gas-division system that is known to be linear with a span gas. Gas-cylinders, gas-division systems, and span gases that you use for reference values must meet the specifications of § 1065.750.

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Table 1 of §1065.307—Measurement systems that require linearity checks

| Measurement System   | Quantity  | When to perform linearity check <sup>a</sup> | Linearity Criteria <sup>c</sup>   |
|--|-----------|--|---|
| Engine speed   | $f_n$     | After major maintenance                      | $ a_0  \leq 0.05 \% \times f_{nmax}, 0.98 \leq a_1 \leq 1.02$<br>$SE \leq 2 \% \times f_{nmax}, r^2 \geq 0.990$                     |
| Engine torque  | $T$       | Every 12 months                              | $ a_0  \leq 1 \% \times T_{max}, 0.98 \leq a_1 \leq 1.02$<br>$SE \leq 2 \% \times T_{max}, r^2 \geq 0.990$                          |
| Fuel flow rate   | $\dot{m}$ | Every 12 months <sup>b</sup>                 | $ a_0  \leq 1 \% \times \dot{m}_{max}, 0.98 \leq a_1 \leq 1.02$ <sup>d</sup><br>$SE \leq 2 \% \times \dot{m}_{max}, r^2 \geq 0.990$ |
| Intake-air flow rate                                       | $\dot{n}$ | After major maintenance <sup>b</sup>         | $ a_0  \leq 1 \% \times \dot{n}_{max}, 0.98 \leq a_1 \leq 1.02$ <sup>d</sup><br>$SE \leq 2 \% \times \dot{n}_{max}, r^2 \geq 0.990$ |
| Dilution air flow rate                                     | $\dot{n}$ | After major maintenance <sup>b</sup>         | $ a_0  \leq 1 \% \times \dot{n}_{max}, 0.98 \leq a_1 \leq 1.02$<br>$SE \leq 2 \% \times \dot{n}_{max}, r^2 \geq 0.990$              |
| Diluted exhaust flow rate                                  | $\dot{n}$ | After major maintenance <sup>b</sup>         | $ a_0  \leq 1 \% \times \dot{n}_{min}, 0.98 \leq a_1 \leq 1.02$<br>$SE \leq 2 \% \times \dot{n}_{max}, r^2 \geq 0.990$              |
| Raw exhaust flow rate                                      | $\dot{n}$ | Every 12 months <sup>b</sup>                 | $ a_0  \leq 1 \% \times \dot{n}_{max}, 0.98 \leq a_1 \leq 1.02$ <sup>d</sup><br>$SE \leq 2 \% \times \dot{n}_{max}, r^2 \geq 0.990$ |
| Sample flow rate   | $\dot{n}$ | Every 12 months <sup>b</sup>                 | $ a_0  \leq 1 \% \times \dot{n}_{max}, 0.98 \leq a_1 \leq 1.02$<br>$SE \leq 2 \% \times \dot{n}_{max}, r^2 \geq 0.990$              |
| Gas dividers   | $x$       | Every 12 months                              | $ a_0  \leq 0.5 \% \times x_{max}, 0.98 \leq a_1 \leq 1.02$<br>$SE \leq 2 \% \times x_{max}, r^2 \geq 0.990$                        |
| Continuous constituent concentration (e.g., gas analyzers) | $x$       | Every 6 months                               | $ a_0  \leq 0.5 \% \times x_{max}, 0.98 \leq a_1 \leq 1.02$<br>$SE \leq 2 \% \times x_{max}, r^2 \geq 0.990$                        |

<sup>a</sup> Perform a linearity check more frequently based upon the instrument manufacturer's recommendations.

<sup>b</sup> These linearity checks are not required for systems that pass the flow-rate check for diluted exhaust as described in §1065.341 (the propane check) or for systems that agree within  $\pm 2\%$  based on a chemical balance of carbon or oxygen of the intake air, fuel, and exhaust.

<sup>c</sup> "max" refers to the maximum value expected during a test—the maximum value used for the linearity check.

<sup>d</sup>  $a_0$  and  $a_1$  for these quantities are required only if the actual value of the quantity is required, versus a signal that is only linearly proportional to the actual value.

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**§ 1065.308 Continuous gas analyzer system response check.**

(a) *Scope and frequency.* Perform this check after installing or replacing a gas analyzer that you use for continuous sampling. Also perform this check if

you reconfigure your system in a way that would change system response. For example, you add a significant volume to the transfer lines by increasing their length or adding a filter. As another example, you change the frequency at which you sample and record gas analyzer concentrations.

(b) *Measurement principles.* This check is an overall system response check for continuous analyzers. It evaluates two aspects of instrument response, as follows:

(1) *Uniform response.* To determine a single gas concentration, you may combine more than one gas

measurement. For example, you may measure an interference gas and use its value in an algorithm to compensate the value of another measured gas concentration. The response of the interference gas instrument must match the response of the instrument that it is compensating.

(2) *Overall system response.* The overall system response and the system's recording frequency must be properly matched. Gas analyzer systems must be optimized such that their overall response to a rapid change in concentration is recorded at an appropriate frequency to prevent loss of information.

(c) *System requirements.* The response check is evaluated by two performance criteria, as follows:

(1) Compensated signals must have a uniform rise and fall during the full response to a step change. During a system response to a rapid change in multiple gas concentrations, the shape of any compensated signal must have no more than one inflection point. In other words, the second derivative of any compensated signal must change sign from negative (–) to positive (+) no more than once whenever a multi-component step increase occurs, and the second derivative must change sign from positive (+) to negative (–) no more than once whenever a multi-component step decrease occurs.

(2) The product of the mean rise time and the sampling frequency must be at least 5, and the product of the mean fall time and the sampling frequency must be at least 5.

(d) *Procedure.* Use the following procedure to check the response of your continuous gas analyzer system.

(1) *Instrument setup.* Follow the analyzer system manufacturers' start-up and operation instructions. Adjust the system as needed to optimize performance.

(2) *Equipment setup.* Connect a zero air source to one inlet of a fast acting 3-way valve (2 inlets, 1 outlet). Connect an NO, CO, CO<sub>2</sub>, C<sub>3</sub>H<sub>8</sub> quad-blend span gas to the other valve inlet. Connect the valve outlet to a heated line at 50 °C, and connect the heated line outlet to the inlet of a 50 °C gas bubbler filled with distilled water. Connect the bubbler outlet to another heated line at 100 °C. Connect the outlet of the 100 °C line to the gas analyzer system's probe or to the overflow fitting between the probe and transfer line.

(3) *Data collection.*

(i) Switch the valve to flow zero gas.

(ii) Allow for stabilization, accounting for transport delays and the slowest instrument's full response.

(iii) Start recording data at the frequency you would during emission testing.

(iv) Switch the valve to flow span gas.

(v) Allow for transport delays and the slowest instrument's full response.

(vi) Repeat the steps in paragraphs (d)(3)(i) through (v) of this section to record seven full cycles, ending with zero gas flowing to the analyzers.

(vii) Stop recording.

(4) *Performance evaluation.*

(i) *Uniform response.* Compute the second derivative for any compensated analyzer signals. The second derivative must change sign from negative (–) to positive (+) no more than once whenever span gas was flowed, and the second derivative must change sign from positive (+) to negative (–) no more than once whenever zero gas was flowed. If it did, determine if the cause was an interference gas compensation signal. If you can positively demonstrate that any failure was not caused by an interference compensation signal, then the analyzer system passes this test. Otherwise, adjust the compensation algorithms' time-alignment and/or dispersion to result in a uniform rise and fall during this performance check.

(ii) *Rise time, fall time, and recording frequency.* Calculate the mean rise time, T<sub>10-90</sub> and mean fall time T<sub>90-10</sub> for each of the analyzers. Multiply these times (in s) by their respective recording frequencies in Hertz (1/s). The value for each result must be at least 5. If the value is less than 5, increase the recording frequency or adjust the flows or design of the sampling system to increase the rise time and/or fall time. You may not use interpolation to increase the number of recorded values. In other words, each recorded value must be a unique record of the actual analyzer signal.

### Measurement of Engine Parameters and Ambient Conditions

#### § 1065.310 Torque calibration.

Calibrate your torque measurement system upon initial installation, and use good engineering judgment to re-calibrate your system. Calibrate torque with the lever-arm dead-weight technique or the transfer technique, as described in paragraphs (a) and (b) of this section. We define the NIST "true value" torque as the torque calculated by taking the product of a weight or force traceable to NIST and a sufficiently accurate horizontal distance along a lever arm, corrected for the lever arm's hanging torque.

(a) The lever-arm dead-weight technique involves placing known weights at a known horizontal distance

from the torque-measuring device's center of rotation. You need two types of equipment:

(1) *Calibration weights or force.* This technique requires calibration weights or a force apparatus traceable to NIST standards. Use at least six calibration points for each applicable torque-measuring range, spacing the points about equally over the range.

(i) For calibration weights, determine their force by multiplying their NIST-traceable masses by your local acceleration of Earth's gravity. The local acceleration of gravity,  $a_g$  at your latitude, longitude, and elevation may be determined by entering your position and elevation data into the United States' National Oceanographic and Atmospheric Administration's surface gravity prediction Web site: [http://www.ngs.noaa.gov/cgi-bin/grav\\_pdx.prl](http://www.ngs.noaa.gov/cgi-bin/grav_pdx.prl). If this Web site is unavailable, you may use the equations in § 1065.630, which return your local acceleration of gravity based on your latitude and elevation. Make sure the lever arms are perpendicular to gravity.

(ii) [Reserved]

(2) *Lever arm.* Apply the calibration weights or force apparatus to the torque-sensing device through a lever arm. The length of the lever arm, from the point where the calibration force or weights are applied to the dynamometer centerline, must be known accurately enough to allow the system to meet the linearity criteria in Table 1 of § 1065.307. Take into account the torque-producing effect of the lever arm's mass. You may balance the lever arm's mass to minimize the torque-producing effect.

(b) The transfer technique involves calibrating a master load cell, such as a dynamometer-case load cell. You may calibrate the master load cell with known calibration weights or force at known horizontal distances. Alternatively, you may use a pre-calibrated master load cell to transfer this calibration to the device that measures engine torque. The transfer technique involves the following three main steps:

(1) Pre-calibrate a master load cell using weights or force and a lever arm as specified in paragraph (a) of this section. Run or vibrate the dynamometer during this calibration to reduce frictional static hysteresis.

(2) The measured horizontal distance from the dynamometer centerline to the point where you apply a weight or force must be accurate to within  $\pm 0.5\%$ . Balance the arms or know their net hanging torque to within  $\pm 0.5\%$ .

(3) Transfer calibration from the case or master load cell to the torque-

measuring device with the dynamometer operating at a constant speed. Calibrate the torque-measurement device's readout to the master load cell's torque readout at a minimum of six loads spaced about equally across the full useful ranges of both measurement devices. Transfer the calibration so it meets the linearity criteria in Table 1 of § 1065.307.

**§ 1065.315 Pressure, temperature, and dewpoint calibration.**

(a) Follow the measurement-system manufacturer's instructions and recommended frequency for calibrating pressure, temperature, and dewpoint, upon initial installation and use good engineering judgment to re-calibrate, as follows:

(1) *Pressure.* We recommend temperature-compensated, digital-pneumatic, or deadweight pressure calibrators, with data-logging capabilities to minimize transcription errors.

(2) *Temperature.* We recommend digital dry-block or stirred-liquid temperature calibrators, with datalogging capabilities to minimize transcription errors.

(3) *Dewpoint.* We recommend a minimum of three different temperature-equilibrated and temperature-monitored calibration salt solutions in containers that seal completely around the dewpoint sensor.

(b) You may remove system components for off-site calibration.

**Flow-Related Measurements**

**§ 1065.320 Fuel flow calibration.**

(a) Follow the measurement-system manufacturer's instructions for calibrating a fuel flow meter upon initial installation and use good engineering judgment to re-calibrate. We recommend using a scale and a stopwatch.

(b) You may also develop a procedure based on a chemical balance of carbon or oxygen in engine exhaust.

(c) You may remove system components for off-site calibration. When installing a flow meter with an off-site calibration, we recommend that you consider the effects of your tubing configuration upstream and downstream of your flow meter.

**§ 1065.325 Intake flow calibration.**

(a) Follow the measurement-system manufacturer's instructions for calibrating intake-air flow upon initial installation, and use good engineering judgment to re-calibrate. We recommend using a calibration subsonic venturi.

(b) You may remove system components for off-site calibration. When installing a flow meter with an off-site calibration, we recommend that you consider the effects of your tubing configuration upstream and downstream of your flow meter.

(c) If you use a subsonic venturi for intake flow measurement, we recommend that you calibrate it as described in § 1065.340.

**§ 1065.330 Exhaust flow calibration.**

(a) Follow the measurement-system manufacturer's instructions for calibrating exhaust flow upon initial installation, and use good engineering judgment to re-calibrate. We recommend that you use a calibration subsonic venturi and simulate exhaust temperatures by incorporating a heat exchanger between the calibration meter and your exhaust-flow meter.

(b) You may remove system components for off-site calibration. When installing a flow meter with an off-site calibration, we recommend that you consider the effects of your tubing configuration upstream and downstream of your flow meter.

(c) If you use a subsonic venturi for intake flow measurement, we recommend that you calibrate it as described in § 1065.340.

**§ 1065.340 Diluted exhaust flow (CVS) calibration.**

(a) *Overview.* This section describes how to calibrate flow meters for diluted exhaust constant-volume sampling (CVS) systems.

(b) *Scope and frequency.* Perform this calibration while the flow meter is installed in its permanent position. Perform this calibration after you change any part of the flow configuration upstream or downstream of the flow meter that may affect the flow meter calibration. Perform this calibration upon initial CVS installation and whenever corrective action does not resolve a failure to meet the diluted exhaust flow check in § 1065.341.

(c) *Reference flow meter.* Calibrate a CVS flow meter using a reference subsonic venturi flow meter. Long radius ASME/NIST flow nozzles are acceptable. Use a reference flow meter that is within  $\pm 1$  % NIST traceability. Use this reference flow meter's response to flow as the reference value for CVS flow meter calibration.

(d) *Configuration.* Do not use an upstream screen or other restriction that could affect the flow ahead of the reference flow meter, unless the flow meter has been calibrated with such a restriction.

(e) *PDP calibration.* Calibrate a PDP to determine a flow versus PDP speed

equation that accounts for flow leakage across sealing surfaces in the PDP as a function of PDP inlet pressure. Calibrate a PDP flow meter as follows:

(1) Connect the system as shown in Figure 1 of this section.

(2) Eliminate leaks between the calibration flow meter and the PDP such that total leakage is less than 0.3 % of the lowest flow point; for example, at the highest restriction and lowest PDP-speed point.

(3) While the PDP operates, maintain a constant temperature at the PDP inlet within  $\pm 2$  % of the average absolute inlet temperature,  $\bar{T}_{in}$ .

(4) Set the PDP speed to the first speed point at which you intend to calibrate.

(5) Set the variable restrictor to its wide-open position.

(6) Operate the PDP for at least 3 min to stabilize the system. Continue operating the CFV and record the mean of at least 25 measurements of each of the following quantities:

(i) Flow rate of the reference flow meter,  $n$ .

(ii) Temperature at the PDP inlet,  $T_{in}$ .

(iii) Static absolute pressure at the PDP inlet,  $P_{in}$ .

(iv) Static absolute pressure at the PDP outlet,  $P_{out}$ .

(v) PDP speed,  $f_{PDP}$ .

(7) Incrementally close the restrictor valve to decrease the absolute pressure at the inlet to the PDP,  $P_{in}$ .

(8) Repeat the steps in paragraphs (e)(6) and (e)(7) of this section to record data at a minimum of six restrictor positions reflecting the full range of possible in-use pressures at the PDP inlet.

(9) Calibrate the PDP by using the collected data and the equations in § 1065.640.

(10) Repeat the steps in paragraphs (e)(6) through (e)(9) of this section for each speed that you operate the PDP.

(11) Use the equations in § 1065.642 to determine the PDP flow equation for emission testing.

(12) Verify the calibration by performing a CVS check (*i.e.*, propane check) as described in § 1065.341

(13) Use the flow equation to determine PDP flow during emission testing. Do not use the PDP below the lowest inlet pressure tested during calibration.

(f) *CFV calibration.* Calibrate a CFV to verify its discharge coefficient,  $C_d$  and the lowest inlet pressure at which you may use your CFV. Calibrate a CFV flow meter as follows:

(1) Connect the system as shown in Figure 1 of this section.

(2) Eliminate leaks between the calibration flow meter and the CFV such

that total leakage is less than 0.3 % of total flow at the highest restriction.

(3) While the CFV operates, maintain a constant temperature at the CFV inlet within  $\pm 2$  % of the average absolute inlet temperature,  $\bar{T}_{in}$ .

(4) Start the blower downstream of the CFV.

(5) Set the variable restrictor to its wide-open position.

(6) Operate the CFV for at least 3 min to stabilize the system. Continue operating the CFV and record the mean of at least 25 measurements of each of the following quantities:

(i) Flow rate of the reference flow meter,  $\dot{n}$ .

(ii) Optionally, dewpoint of the calibration air,  $T_{dew}$ . See § 1065.640 for permissible assumptions.

(iii) Temperature at the venturi inlet,  $T_{in}$ .

(iv) Static absolute pressure at the venturi inlet,  $P_{in}$ .

(7) Incrementally close the restrictor valve to decrease the absolute pressure at the inlet to the CFV,  $P_{in}$ .

(8) Repeat the steps in paragraphs (f)(6) and (f)(7) of this section to record data at a minimum of ten restrictor positions, such that you test the full range of inlet pressures expected during testing.

(9) Determine  $C_d$  and the lowest inlet pressure at which you may use your CFV as described in § 1065.640.

(10) Verify the calibration by performing a CVS check (*i.e.*, propane check) as described in § 1065.341.

(11) Use the  $C_d$  to determine CFV flow during an emission test. Do not use the CFV below the lowest inlet pressure tested during calibration.

(g) *SSV calibration.* Calibrate an SSV flow meter as follows: Calibrate an SSV to determine its calibration coefficient,  $C_d$  for the range of inlet pressures over which you may use your SSV. Calibrate an SSV flow meter as follows:

(1) Connect the system as shown in Figure 1 of this section.

(2) Eliminate leaks between the calibration flow meter and the SSV such that total leakage is less than 0.3 % of total flow at the highest restriction.

(3) While the SSV operates, maintain a constant temperature at the SSV inlet within  $\pm 2$  % of the average absolute inlet temperature,  $\bar{T}_{in}$ .

(4) Start the blower downstream of the SSV.

(5) Set the variable restrictor or variable-speed blower to a flow rate greater than the greatest flow rate expected during testing. Because we do not allow extrapolation of flow rates beyond calibrated values, we recommend that you ensure that the SSV throat Reynolds number ( $Re\#$ ) at your greatest calibrated flow rate is greater than the maximum  $Re\#$  expected during testing.

(6) Operate the SSV for at least 3 min to stabilize the system. Continue

operating the SSV and record the mean of at least 25 measurements of each of the following quantities:

(i) Flow rate of the reference flow meter,  $\dot{n}$ .

(ii) Optionally, dewpoint of the calibration air,  $T_{dew}$ . See § 1065.640 for permissible assumptions.

(iii) Temperature at the venturi inlet,  $T_{in}$ .

(iv) Static absolute pressure at the venturi inlet,  $P_{in}$ .

(v) Static absolute pressure at the venturi throat,  $P_{th}$ .

(7) Incrementally close the restrictor valve or decrease the blower speed to decrease the flow rate.

(8) Repeat the steps in paragraphs (g)(6) through (g)(7) of this section to record data at a minimum of ten flow rates.

(9) Determine a functional form of  $C_d$  versus  $Re\#$  by using the collected data and the equations in § 1065.640.

(10) Verify the calibration by performing a CVS check (*i.e.*, propane check) as described in § 1065.341 using the new  $C_d$  versus  $Re\#$  equation.

(11) Use the SSV only between the minimum and maximum calibrated flow rates.

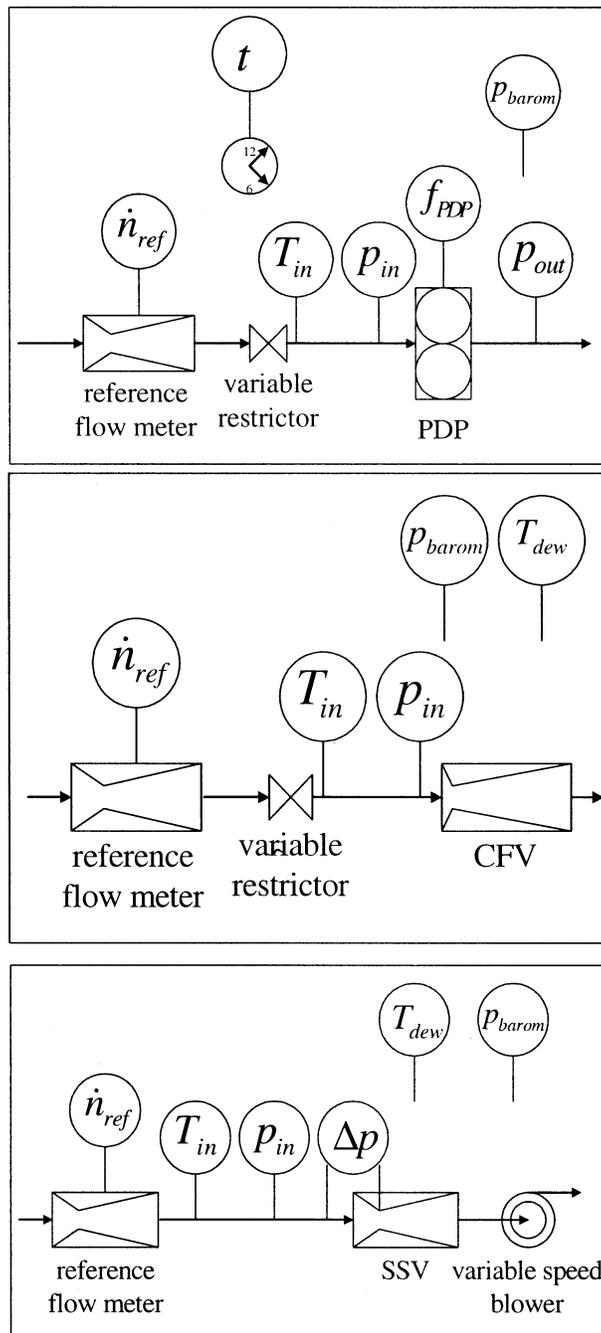
(12) Use the equations in § 1065.642 to determine SSV flow during a test.

(h) *Ultrasonic flow meter calibration.*

[Reserved]

BILLING CODE 6560-50-P

Figure 1 of §1065.340—Schematic diagrams for diluted exhaust flow (CVS) calibration.



BILLING CODE 6560-50-C

**§ 1065.341 CVS and batch sampler verification (i.e. propane check).**

(a) Perform this check to determine if there is a discrepancy in your measured values of diluted exhaust flow. You may also perform this check to determine if there is a discrepancy in a batch sampling system that extracts a sample from a CVS. Failure of this check might indicate that one or more of the

following problems might require corrective action:

- (1) *Incorrect analyzer calibration.* Recalibrate FID analyzer or repair or replace analyzer.
- (2) *Leaks.* Inspect CVS tunnel, connections, and fasteners and repair or replace components.
- (3) *Poor mixing.* Perform the check as described in paragraph (b) of this section while traversing sampling probe across diameter of tunnel, vertically and horizontally. If analyzer response

indicates a deviation that exceeds  $\pm 2\%$  of the mean measured concentration, consider operating the CVS at a higher flow rate or installing a mixing plate or orifice to improve mixing.

(4) *Hydrocarbon contamination in the sample system.* Perform the hydrocarbon contamination check as described in § 1065.520.

(5) *Change in CVS calibration.* Perform an in-situ calibration of the

CVS flow meter as described in § 1065.340.

(6) *Other problems with the CVS or sampling check hardware or software.* Inspect CVS system, the CVS check hardware, and your software for discrepancies.

(b) *C<sub>3</sub>H<sub>8</sub> check.* This check uses either a reference mass or a reference flow rate of C<sub>3</sub>H<sub>8</sub> as a tracer gas in a CVS. Note that if you use a reference flow rate, you might have to account for the non-ideal gas behavior of C<sub>3</sub>H<sub>8</sub> in your reference flow meter. You inject the reference C<sub>3</sub>H<sub>8</sub> into the CVS and then calculate the mass you injected using your NMHC measurements and CVS flow rate measurements.

(c) Prepare for this check as follows:

(1) Obtain a cylinder charged with C<sub>3</sub>H<sub>8</sub>. Determine the reference cylinder's full weight within ±0.5% if you use a reference mass instead of a reference flow rate.

(2) Select appropriate flow rates for the CVS and C<sub>3</sub>H<sub>8</sub>.

(3) Select a C<sub>3</sub>H<sub>8</sub> injection port in the CVS. Select the port location to be as close as practical to the location where you introduce engine exhaust into the CVS. Connect the C<sub>3</sub>H<sub>8</sub> cylinder to the injection system.

(4) Operate and stabilize the CVS.

(5) Preheat any heat exchangers in the sampling system.

(6) Allow heated components such as sample lines, filters, and pumps to stabilize at operating temperature.

(7) You may purge your NMHC sampling system during stabilization.

(8) If applicable, perform a vacuum side leak check of the NMHC sampling system as described in § 1065.345.

(9) You may also conduct any other calibrations or performance checks on any equipment or analyzers.

(d) Zero, span, and check for contamination of the NMHC sampling system, as follows:

(1) Select the lowest NMHC analyzer range that can measure the C<sub>3</sub>H<sub>8</sub> concentration expected for your CVS and C<sub>3</sub>H<sub>8</sub> flow rates.

(2) Zero the NMHC analyzer using zero air introduced at the analyzer port.

(3) Span the NMHC analyzer using C<sub>3</sub>H<sub>8</sub> span gas introduced at the analyzer port.

(4) Overflow zero air at the NMHC probe or into a fitting between the NMHC probe and the transfer line.

(5) Measure the stable NMHC concentration of the NMHC sampling system as overflow zero air flows.

(6) If the overflow NMHC concentration exceeds 2% of the expected C<sub>3</sub>H<sub>8</sub> concentration, determine the source of the contamination and take corrective action, such as cleaning

the system or replacing contaminated portions. Do not proceed until contamination is eliminated.

(7) If the overflow NMHC concentration does not exceed 2% of the expected C<sub>3</sub>H<sub>8</sub> concentration, record this value as  $x_{\text{NMHCpre}}$  and use it to correct for NMHC contamination as described in § 1065.660.

(e) Perform the propane check as follows:

(1) For batch NMHC sampling, connect clean storage media, such as evacuated bags.

(2) Operate NMHC measurement instruments according to the instrument manufacturer's instructions.

(3) If you choose to correct for dilution air background concentrations of NMHC, measure and record background NMHC.

(4) Zero any integrating devices.

(5) Begin sampling, and start any flow integrators.

(6) Release the contents of the propane reference cylinder and the rate you selected. If you use a reference flow rate C<sub>3</sub>H<sub>8</sub>, start integrating this flow rate.

(7) Continue to release the cylinder's contents for a duration of time that is at least as long as your shortest test interval for emission testing.

(8) Shut off the C<sub>3</sub>H<sub>8</sub> reference cylinder and continue sampling until you have accounted for time delays due to sample transport delays and analyzer response times.

(9) Stop sampling, and stop any integrators.

(f) Perform post-test procedure as follows:

(1) If you used batch sampling, analyze batch samples as soon as practical.

(2) After analyzing NMHC correct for drift, contamination, and background.

(3) Calculate total C<sub>3</sub>H<sub>8</sub> mass based on your CVS and NMHC data as described in § 1065.650 and § 1065.660 using of the molar mass of C<sub>3</sub>H<sub>8</sub>,  $M_{\text{C}_3\text{H}_8}$  instead of the molar mass of NMHC,  $M_{\text{NMHC}}$ .

(4) If you use a reference mass, determine the cylinder's post-test weight within ±0.5%, and determine the C<sub>3</sub>H<sub>8</sub> reference mass by subtracting empty cylinder weight from the full cylinder weight.

(5) Subtract the reference C<sub>3</sub>H<sub>8</sub> mass from your calculated mass. If this difference is within ±2% of the reference mass, the CVS passes this check. If not, take corrective action as described in paragraph (a) of this section.

(g) *Batch sampler check.* You may repeat the C<sub>3</sub>H<sub>8</sub> check to check a batch sampler, such as a PM secondary dilution system.

(1) Configure your NMHC sampling system to extract a sample near the

location of your batch sampler's storage media (e.g., PM filter). If the absolute pressure at this location is too low to extract an NMHC sample, you may sample NMHC from the batch sampler pump's exhaust. Use caution when sampling from pump exhaust because an acceptable pump leak downstream of a batch sampler flow meter will cause a false failure of the C<sub>3</sub>H<sub>8</sub> check.

(2) Repeat the C<sub>3</sub>H<sub>8</sub> check described in this section, sampling NMHC from your batch sampler.

(3) Calculate C<sub>3</sub>H<sub>8</sub> mass taking into account any secondary dilution from your batch sampler.

(4) Subtract the reference C<sub>3</sub>H<sub>8</sub> mass from your calculated mass. If this difference is within ±5% of the reference mass, the batch sampler passes this check. If not, take corrective action as described in paragraph (a) of this section.

#### § 1065.345 Vacuum-side leak check.

Within seven days before each test, check for vacuum-side leaks as described in this section. Check for vacuum-side leaks using one of the following two procedures:

(a) Perform a flow-rate leak-test as follows:

(1) For a given sampling system, seal the probe end of the system by taking one of the following steps:

(i) Cap or plug the end of the sample probe

(ii) Disconnect the transfer line at the probe and cap or plug the transfer line.

(iii) Close a leak-tight valve in line between a probe and transfer line.

(2) Operate each analyzer pump. After stabilizing the system, verify that the flow through each analyzer is less than 0.5% of the in-use flow rate. You may use nominal analyzer and bypass flows to estimate in-use flow.

(b) Perform an over-flow leak-test as follows:

(1) For a given sampling system, route overflow span gas to one of the following locations in the sampling system:

(i) The end of the sample probe

(ii) Disconnect the transfer line and route to the end of the transfer line.

(iii) A three-way valve installed in-line between a probe and transfer line.

(2) After stabilizing the system, verify that the measured span gas concentration is within the measurement accuracy and repeatability of the analyzer. Note that a measured value lower than expected may be an indication of a leak, but a higher than expected concentration may be an indication of a problem with the span gas or the analyzer itself. A higher than expected concentration does not indicate a leak.

**CO AND CO<sub>2</sub> MEASUREMENTS****§ 1065.350 H<sub>2</sub>O interference check for CO<sub>2</sub> NDIR analyzers.**

(a) *Scope and frequency.* If you measure CO<sub>2</sub> using an NDIR analyzer, check for H<sub>2</sub>O interference after initial analyzer installation and after any major maintenance.

(b) *Measurement principles.* H<sub>2</sub>O can interfere with an NDIR analyzer's response for CO<sub>2</sub>. If your NDIR analyzer uses compensation algorithms that utilize measurements of other gases to meet this interference check, simultaneously conduct such measurements to test the algorithms during the analyzer interference check.

(c) *System requirements.* A CO<sub>2</sub> NDIR analyzer must have an H<sub>2</sub>O interference that is less than 2% of the lowest flow-weighted average CO<sub>2</sub> concentration expected during testing, though we strongly recommend a lower interference of less than 1%.

(d) *Procedure.* Perform the interference check as follows:

(1) Start, operate, zero, and span the CO<sub>2</sub> NDIR analyzer according to the instrument manufacturer's instructions.

(2) Create a water-saturated test gas by bubbling zero air that meets the specifications in § 1065.750 through distilled water in a sealed vessel at (25±10) °C.

(3) Upstream of any sample dryer used during testing, introduce the water-saturated test gas.

(4) Allow time for the analyzer response to stabilize. Stabilization time may include time to purge the transfer line and to account for analyzer response.

(5) While the analyzer measures the sample's concentration, record its output for 60 s at a nominal frequency of 5 Hz to record 300 data points. Calculate the arithmetic mean of these 300 points.

(e) If the arithmetic mean of the 300 points is less than 2% of the flow-weighted average concentration of CO<sub>2</sub> expected at the standard, then the analyzer meets the interference check.

(f) You may use a CO<sub>2</sub> NDIR analyzer that you determine does not meet this performance check, as long as you meet all the following criteria:

(1) You try to correct the problem.

(2) The measurement deficiency does not affect your ability to show that your engines comply with all applicable emission standards.

**§ 1065.355 H<sub>2</sub>O and CO<sub>2</sub> interference check for CO NDIR analyzers.**

(a) *Scope and frequency.* If you measure CO using an NDIR analyzer, check for H<sub>2</sub>O and CO<sub>2</sub> interference after

initial analyzer installation and after any major maintenance.

(b) *Measurement principles.* H<sub>2</sub>O and CO<sub>2</sub> can positively interfere with an NDIR analyzer by causing a response similar to CO. If your NDIR analyzer uses compensation algorithms that utilize measurements of other gases to meet this interference check, simultaneously conduct such measurements to test the algorithms during the analyzer interference check.

(c) *System requirements.* A CO NDIR analyzer must have combined H<sub>2</sub>O and CO<sub>2</sub> interference that is less than 2% of the flow-weighted average concentration of CO expected at the standard, as measured in paragraph (d) of this section, though we strongly recommend a lower interference of less than 1%.

(d) *Procedure.* Perform the interference check as follows:

(1) Start, operate, zero, and span the CO NDIR analyzer according to the instrument manufacturer's instructions.

(2) Create a water-saturated CO<sub>2</sub> test gas by bubbling a CO<sub>2</sub> span gas through distilled water in a sealed vessel at (25±10) °C.

(3) Upstream of any sample dryer used during testing, introduce the water-saturated CO<sub>2</sub> test gas.

(4) Allow time for the analyzer response to stabilize. Stabilization time may include time to purge the transfer line and to account for analyzer response.

(5) While the analyzer measures the sample's concentration, record its output at its nominal frequency to record 300 data points. Calculate the arithmetic mean of these 300 points.

(6) Multiply this mean by the ratio of expected CO<sub>2</sub> to span gas CO<sub>2</sub> concentration. In other words, estimate the flow-weighted average dry concentration of CO<sub>2</sub> expected during testing, and then divide this value by the concentration of CO<sub>2</sub> in the span gas used for this check. Then multiply this ratio by the mean of the 300 values recorded during this check.

(e) If the result of (6) is less than 2% of the flow-weighted average concentration of CO expected at the standard, then the analyzer meets the interference check.

(f) You may use a CO NDIR analyzer that does not meet this performance check as long as you meet all the following criteria:

(1) You try to correct the problem.

(2) The measurement deficiency does not affect your ability to show that your engines comply with all applicable emission standards.

**HYDROCARBON MEASUREMENTS****§ 1065.360 FID optimization and performance checks.**

(a) *Scope and frequency.* For all FID analyzers, perform the following:

(1) Calibrate a FID upon initial installation and according to good engineering judgment, as described in paragraph (b) of this section. Calibrate on a carbon number basis of one (1), C<sub>1</sub>.

(2) Optimize, a FID's response to various hydrocarbons after initial analyzer installation and after any major maintenance, as described in paragraph (c) of this section.

(3) Determine a FID's CH<sub>4</sub> response factor after initial analyzer installation and after any major maintenance as described in paragraph (d) of this section.

(4) Check CH<sub>4</sub> response once every 12 months.

(b) *Calibration.* Use good engineering judgment to develop a calibration procedure, such as one based on the FID-analyzer manufacturer's instructions and recommended frequency for calibrating the FID. Alternately, you may remove system components for off-site calibration. Calibrate using a C<sub>3</sub>H<sub>8</sub>, balance synthetic air, calibration gas that meets the specifications of § 1065.750. Calibrate on a carbon number basis of one (1), C<sub>1</sub>. For example, if you use a C<sub>3</sub>H<sub>8</sub> span gas of concentration 200 µmol/mol, span the FID to respond with a value of 600 µmol/mol.

(c) *FID Response optimization.* Use good engineering judgement for initial instrument start-up and basic operating adjustment using FID fuel and zero air. Heated FIDs must be at their specified operating temperature. Optimize FID response at the operating range expected to be used during emission testing. Optimization involves adjusting flows and pressures to minimize response variations to different hydrocarbon species that are expected to be in the exhaust. Use good engineering judgment to trade off peak FID response to propane-in-air to achieve minimal response variations to different hydrocarbons. A good example of trading off response to propane for relative responses to other hydrocarbon species is given in Society of Automotive Engineers (SAE) Paper No. 770141, "Optimization of Flame Ionization Detector for Determination of Hydrocarbon in Diluted Automotive Exhausts;" author Glenn D. Reschke (incorporated by reference in § 1065.1010). After the optimum flow rates have been determined, record them for future reference.

(d) *CH<sub>4</sub> response factor determination.* Since FID analyzers generally do not have a 1.00 CH<sub>4</sub> response factor, determine each FID analyzer's CH<sub>4</sub> response factor after FID optimization. Because we do not limit the range of FID analyzer's  $RF_{CH_4}$ , you must use the most recent  $RF_{CH_4}$  that you measured according to this section. Use the most recent  $RF_{CH_4}$  in the calculations for NMHC determination as described in § 1065.660. These calculations compensate for CH<sub>4</sub> response. Determine a FID analyzer's response CH<sub>4</sub> factor as follows:

(1) Select a propane (C<sub>3</sub>H<sub>8</sub>) calibration gas that meets the specifications of § 1065.750 and has a concentration typical of the flow-weighted average concentration expected at the hydrocarbon standard. Record the calibration concentration of the gas.

(2) Select a methane (CH<sub>4</sub>) calibration gas that meets the specifications of § 1065.750 and has a concentration typical of the flow-weighted average concentration expected at the hydrocarbon standard. Record the calibration concentration of the gas.

(3) Start and operate the FID analyzer according to the manufacturer's instructions.

(4) Confirm that the FID analyzer has been calibrated using C<sub>3</sub>H<sub>8</sub>. Calibrate on a carbon number basis of one (1), C<sub>1</sub>. For example, if you use a C<sub>3</sub>H<sub>8</sub> span gas of concentration 200 µmol/mol, span the FID to respond with a value of 600 µmol/mol.

(5) Zero the FID with zero air that meets the specifications of § 1065.750.

(6) Span the FID with the calibration gas that you selected in paragraph (d)(1) of this section.

(7) Introduce at the inlet of the FID analyzer the CH<sub>4</sub> calibration gas that you selected in paragraph (d)(2) of this section.

(8) Allow time for the analyzer response to stabilize. Stabilization time may include time to purge the analyzer and to account for its response.

(9) While the analyzer measures the CH<sub>4</sub> concentration, record its output for 60 s at a nominal frequency of 5 Hz to record 300 data points. Calculate the arithmetic mean of these 300 points.

(10) Divide the mean measured concentration by the recorded calibration concentration of the CH<sub>4</sub> calibration gas. The result is the FID analyzer's response factor for CH<sub>4</sub>,  $RF_{CH_4}$ .

(e) *FID CH<sub>4</sub> response check.* Check the FID CH<sub>4</sub> response by performing the following:

(1) Perform the CH<sub>4</sub> response factor determination as described in paragraph (d) of this section.

(2) If the CH<sub>4</sub> response factor is within ±5% of its most recently determined value, the FID passes the FID flow check.

(3) If the FID does not pass this check, first verify that the pressures and flow rates of FID fuel, burner air, and sample are each within ±0.5% of their most recently recorded values. These values are recorded each time you conduct a FID response optimization as described in paragraph (c) of this section. You may adjust these flows as necessary.

(4) Repeat the CH<sub>4</sub> response factor determination as described in paragraph (d) of this section.

(5) If the pressures and/or flows are correct, but the CH<sub>4</sub> response factor is not within ±5% of its most recently determined value, then repeat the FID response optimization as described in paragraph (c) of this section.

(6) Repeat the CH<sub>4</sub> response factor as described in paragraph (d) of this section.

(7) Use this CH<sub>4</sub> response factor,  $RF_{CH_4}$ , in the calculations for NMHC determination as described in § 1065.660.

#### § 1065.362 Raw exhaust FID O<sub>2</sub> interference check.

(a) *Scope and frequency.* If you use a FID analyzer for raw exhaust measurements, perform an O<sub>2</sub> interference check upon initial installation and after major maintenance.

(b) *Measurement principles.* Changes in O<sub>2</sub> concentration in raw exhaust can affect FID response by changing FID flame temperature. Optimize FID fuel, burner air, and sample flow to meet this check.

(c) *System requirements.* Your FID must meet the O<sub>2</sub> interference check according to ISO 8178-1, Section 8.8.3 (incorporated by reference in § 1065.1002).

#### § 1065.365 Nonmethane cutter penetration fractions determination.

(a) *Scope and frequency.* If you use a FID analyzer and a nonmethane cutter to measure methane (CH<sub>4</sub>), determine the nonmethane cutter's penetration fractions of CH<sub>4</sub>,  $PF_{CH_4}$  and ethane,  $PF_{C_2H_6}$  as described in this section. Perform this check after installing the nonmethane cutter, and within six months after the previous check. This check must be repeated within six months of the activity of the cutter has not deteriorated.

(b) *Measurement principles.* A nonmethane cutter removes nonmethane hydrocarbons from the exhaust stream before the FID analyzer

measures hydrocarbon concentrations. An ideal nonmethane cutter would have  $PF_{CH_4}$  of 1.000, and the penetration fraction for all other hydrocarbons would be 0.000, as represented by  $PF_{C_2H_6}$ . The emission calculations in § 1065.660 use the actual measured values of  $PF_{CH_4}$  and  $PF_{C_2H_6}$  to account for less than ideal nonmethane cutter performance.

(c) *System requirements.* We do not limit penetration fractions to a certain range. However, we do recommend that you optimize a nonmethane cutter by adjusting its catalyst temperature to achieve  $PF_{CH_4} > 0.9$  and  $PF_{C_2H_6} < 0.1$  as determined by paragraph (d) of this section. If we use a nonmethane cutter for testing, it will meet this recommendation. If adjusting catalyst temperature does not result in achieving both of these specifications simultaneously, we recommend that you replace the catalyst. Use the most recently determined penetration values from this section to calculate the concentration of NMHC,  $x_{NMHC}$  as described in § 1065.660.

(d) *Procedure.* Determine penetration fractions as follows:

(1) Select CH<sub>4</sub> and C<sub>2</sub>H<sub>6</sub> analytical gas mixtures that meet the specifications of § 1065.750 with concentrations typical of the flow-weighted average concentrations expected at the hydrocarbon standard.

(2) Start and operate the nonmethane cutter according to the manufacturer's instructions.

(3) Confirm that the FID analyzer meets all of the specifications of § 1065.360.

(4) Start and operate the FID analyzer according to the manufacturer's instructions.

(5) Connect the FID analyzer to the outlet of the nonmethane cutter.

(6) Introduce the CH<sub>4</sub> analytical gas mixture upstream of the nonmethane cutter.

(7) Allow time for the analyzer response to stabilize. Stabilization time may include time to purge the nonmethane cutter and to account for its response.

(8) While the analyzer measures the sample's concentration, record its output for 60 s at a nominal frequency of 5 Hz to record 300 data points. Calculate the arithmetic mean of these 300 points.

(9) Reroute the flow path to bypass the nonmethane cutter and repeat the steps in paragraphs (d)(6) through (d)(8) of this section.

(10) Divide the mean concentration measured through the nonmethane cutter by the mean concentration measured after bypassing the

nonmethane cutter. The result is the CH<sub>4</sub> penetration fraction ( $PF_{CH_4}$ )

(11) Repeat steps in paragraphs (b)(6) through (b)(10) of this section but with the C<sub>2</sub>H<sub>6</sub> analytical gas mixture instead of the CH<sub>4</sub> analytical gas mixture. The result is the C<sub>2</sub>H<sub>6</sub> penetration fraction ( $PF_{C_2H_6}$ ).

## NO<sub>x</sub> MEASUREMENTS

### § 1065.370 CLD CO<sub>2</sub> and H<sub>2</sub>O quench check.

(a) *Scope and frequency.* If you use a CLD analyzer to measure NO<sub>x</sub>, check for H<sub>2</sub>O and CO<sub>2</sub> quench after installing the CLD analyzer and after performing major maintenance.

(b) *Measurement principles.* H<sub>2</sub>O and CO<sub>2</sub> can negatively interfere with a CLD's NO<sub>x</sub> response by collisional quenching, which inhibits the chemiluminescent reaction that a CLD utilizes to detect NO<sub>x</sub>. The calculations in § 1065.672 that are used to determine H<sub>2</sub>O quench account for the water vapor in humidified NO span gas. The procedure and the calculations scale the quench results to the water vapor and CO<sub>2</sub> concentrations expected during testing. If your CLD analyzer uses quench compensation algorithms that utilize H<sub>2</sub>O and/or CO<sub>2</sub> measurement instruments, use these instruments to measure H<sub>2</sub>O and/or CO<sub>2</sub> and evaluate quench with the compensation algorithms applied.

(c) *System requirements.* A CLD analyzer must have a combined H<sub>2</sub>O and CO<sub>2</sub> quench of less than ±2%, though we strongly recommend a quench of ±1%. Combined quench is the sum of the CO<sub>2</sub> quench determined as described in paragraph (d) of this section, plus the H<sub>2</sub>O quench determined as described in paragraph (e) of this section.

(d) *CO<sub>2</sub> quench-check procedure.* Use the following method to determine CO<sub>2</sub> quench, or use good engineering judgment to develop a different protocol:

(1) Use PTFE tubing to make necessary connections.

(2) Connect a pressure-regulated CO<sub>2</sub> span gas to one of the inlets of a three-way valve made of 300 series stainless steel. Use a CO<sub>2</sub> span gas that meets the specifications of § 1065.750 and has a concentration that is approximately twice the maximum CO<sub>2</sub> concentration expected during testing, if available.

(3) Connect a pressure-regulated purified N<sub>2</sub> gas to the valve's other inlet. Use a purified N<sub>2</sub> gas that meets the specifications of § 1065.750.

(4) Connect the valve's single outlet to the balance-gas port of a gas divider that meets the specifications in § 1065.248.

(5) Connect a pressure-regulated NO span gas to the span-port of the gas divider. Use an NO span gas that meets the specifications of § 1065.750.

Attempt to use an NO concentration that is approximately twice the maximum NO concentration expected during testing.

(6) Configure the gas divider such that nearly equal amounts of the span gas and balance gas are blended with each other. Apply viscosity corrections as necessary to appropriately to ensure correct gas divider operation.

(7) While flowing balance and span gases through the gas divider, stabilize the CO<sub>2</sub> concentration downstream of the gas divider and measure the CO<sub>2</sub> concentration with an NDIR analyzer that has been prepared for emission testing. Record this concentration,  $x_{CO_2}$  and use it in the quench check calculations in § 1065.672.

(8) Measure the NO concentration downstream of the gas divider. If your CLD has an operating mode in which it detects only NO, as opposed to total NO<sub>x</sub>, operate the CLD in that operating mode. Record this concentration,  $x_{NO+CO_2}$ , and use it in the quench check calculations in § 1065.672.

(9) Switch the three-way valve so that 100% purified N<sub>2</sub> flows to the gas divider's balance-port inlet. Monitor the CO<sub>2</sub> at the gas divider's outlet until its concentration stabilizes at zero.

(10) Measure NO concentration at the gas divider's outlet. Record this value,  $x_{NO+N_2}$ , and use it in the quench check calculations in § 1065.672.

(11) Calculate CO<sub>2</sub> quench as described in § 1065.672.

(e) H<sub>2</sub>O quench check procedure.

(1) For a CLD analyzer equipped with a sample dryer, as described in § 1065.145(d)(2), you may assume an H<sub>2</sub>O quench value of 0% if you can show that the dryer maintains less than 4 °C dewpoint at its outlet when it receives at its inlet the maximum dewpoint expected during testing. Determine dewpoint as described in § 1065.145(d)(2).

(2) For a CLD analyzer without a dryer, take the following steps to determine H<sub>2</sub>O quench:

(i) If your CLD has an operating mode in which it detects only NO, as opposed to total NO<sub>x</sub>, operate the CLD in that operating mode.

(ii) Measure an NO calibration span gas that meets the specifications of § 1065.750 and is near the maximum concentration expected at the standard. Record this concentration,  $x_{NOdry}$ .

(iii) Bubble the same NO gas through distilled water in a sealed vessel at (25 ±10) °C. Record the vessel water temperature,  $T_{sat}$  and pressure,  $P_{sat}$ . To

prevent subsequent condensation, make sure the humidified sample will not be exposed to temperatures lower than  $T_{sat}$  during transport from the sealed vessel's outlet to the CLD. We recommend heated transfer lines.

(iv) Use the CLD to measure the NO concentration of the humidified span gas and record this value,  $x_{NOwet}$ .

(v) Use the recorded values from this paragraph (e) to calculate the H<sub>2</sub>O quench as described in § 1065.672.

(f) If the sum of the H<sub>2</sub>O quench plus the CO<sub>2</sub> quench is not less than 2%, take corrective action by repairing or replacing the analyzer. Before using a CLD for emission testing, demonstrate that the corrective action resulted in less than 2% combined quench.

### § 1065.372 NDUV analyzer NMHC and H<sub>2</sub>O interference check.

(a) *Scope and frequency.* If you measure NO<sub>x</sub> using an NDUV analyzer, check for H<sub>2</sub>O and hydrocarbon interference after initial analyzer installation and after any major maintenance.

(b) *Measurement principles.* Hydrocarbons and H<sub>2</sub>O can positively interfere with an NDUV analyzer by causing a response similar to NO<sub>x</sub>. If your NDUV analyzer uses compensation algorithms that utilize measurements of other gases to meet this interference check, simultaneously conduct such measurements to test the algorithms during the analyzer interference check.

(c) *System requirements.* A NO<sub>x</sub> NDUV analyzer must have combined H<sub>2</sub>O and hydrocarbon interference that is less than ±2% of the flow-weighted average concentration of NO<sub>x</sub> expected at the standard, as measured in paragraph (d) of this section, though we strongly recommend a lower interference of less than ±1%.

(d) *Procedure.* Perform the interference check as follows:

(1) Start, operate, zero, and span the NO<sub>x</sub> NDUV analyzer according to the instrument manufacturer's instructions.

(2) We recommend that you extract engine exhaust to perform this check. Use a CLD that meets the specifications of subpart C of this part to quantify NO<sub>x</sub> in the exhaust. Use the CLD response as the reference value. Also measure NMHC in the exhaust with a FID analyzer that meets the specifications of subpart C of this part. Use the FID response as the measured hydrocarbon value.

(3) Upstream of any sample dryer used during testing, introduce the engine exhaust to the NDUV analyzer.

(4) Allow time for the analyzer response to stabilize. Stabilization time may include time to purge the transfer

line and to account for analyzer response.

(5) While all analyzers measure the sample's concentration, record 300 data points, and calculate the arithmetic means for the three analyzers.

(6) Subtract the CLD mean from the NDUV mean.

(7) Multiply this difference by the ratio of the flow-weighted average NMHC concentration expected at the standard to the NMHC concentration measured during the performance check.

(e) If the result of (7) is less than  $\pm 2\%$ , then the analyzer meets this interference check.

(f) You may use a  $\text{NO}_x$  NDUV analyzer that demonstrates  $\pm 2\%$  or greater  $\text{H}_2\text{O}$  interference as long as you meet all the following criteria:

(1) You try to correct the problem.

(2) The measurement deficiency does not affect your ability to show that your engines comply with all applicable emission standards.

**§ 1065.374 ZrO<sub>2</sub> NO<sub>x</sub> analyzer NH<sub>3</sub> interference and NO<sub>2</sub> response checks.**

(a) *Scope and frequency.* If you use a ZrO<sub>2</sub> analyzer to measure  $\text{NO}_x$ , check for ammonia interference, NO<sub>2</sub> response, and operation under fuel rich conditions after installing the ZrO<sub>2</sub> analyzer and after major maintenance.

(b) *Measurement principles.* Ammonia (NH<sub>3</sub>) can positively interfere with a ZrO<sub>2</sub> analyzer by causing a response similar to  $\text{NO}_x$ . If your ZrO<sub>2</sub> analyzer uses compensation algorithms that utilize measurements of other gases to meet this interference check, use those analyzers during the NH<sub>3</sub> interference check. Because of the catalytic reactions required for NO<sub>x</sub> measurement via ZrO<sub>2</sub> analyzers, we specify an NO<sub>2</sub> response factor tolerance and an operational check under net fuel-rich exhaust conditions.

(c) *System requirements.* A ZrO<sub>2</sub> analyzer must have an NH<sub>3</sub> interference less than 2% of the flow-weighted average concentration of  $\text{NO}_x$  expected at the standard, though we strongly recommend a lower interference of less than 1%. A ZrO<sub>2</sub> analyzer must also have an NO<sub>2</sub> response factor,  $\text{RF}_{\text{NO}_2}$  of at least 0.95, but not more than 1.05, as measured in paragraph (e) of this section.

(d) *Ammonia interference check.* Check for ammonia interference as follows:

(1) Start, operate, zero, and span the  $\text{NO}_x$  ZrO<sub>2</sub> analyzer according to the instrument manufacturer's instructions.

(2) Select an NH<sub>3</sub> span gas that meets the specifications of § 1065.750.

(3) Introduce the NH<sub>3</sub> span gas at the inlet to the analyzer.

(4) Allow time for the analyzer response to stabilize. Stabilization time may include time to purge the transfer line and to account for analyzer response.

(5) While the analyzer measures the sample's concentration, record its output at its nominal frequency to record 300 data points. Calculate the arithmetic mean of these 300 points.

(6) Multiply this mean by the ratio of expected NH<sub>3</sub> to span gas NH<sub>3</sub> concentration. In other words, estimate the flow-weighted average dry concentration of NH<sub>3</sub> expected during testing, and then divide this value by the concentration of NH<sub>3</sub> in the span gas used for this check. Then multiply this ratio by the mean of the 300 values recorded during this check.

(e) If the result of paragraph (d)(6) is less than 2% of the flow-weighted average concentration of  $\text{NO}_x$  expected at the standard, then the analyzer meets the interference check.

(f) You may use a  $\text{NO}_x$  ZrO<sub>2</sub> analyzer that does not meet this performance check as long as you meet all the following criteria:

(1) You try to correct the problem.

(2) The measurement deficiency does not affect your ability to show that your engines comply with all applicable emission standards.

(g) *NO<sub>2</sub>-response check.* Check for NO<sub>2</sub> response as follows:

(1) Select an NO<sub>2</sub> calibration gas that meets the specifications of § 1065.750. Record the calibration concentration of the gas.

(2) Start, operate, zero, and span the ZrO<sub>2</sub> analyzer according to the manufacturer's instructions.

(3) Introduce the NO<sub>2</sub> calibration gas at the inlet of the ZrO<sub>2</sub> analyzer, and if you use an NO<sub>2</sub> to NO converter upstream of the analyzer during emission testing, introduce the NO<sub>2</sub> upstream of the NO<sub>2</sub> to NO converter.

(4) Allow time for the analyzer response to stabilize. Stabilization time may include time to purge the analyzer and to account for detector response.

(5) While the analyzer measures the sample's concentration, record its output at its nominal frequency to record 300 data points. Calculate the arithmetic mean of these 300 points.

(6) Divide the mean measured value by the recorded calibration concentration of the NO<sub>2</sub> calibration gas. The result is the ZrO<sub>2</sub> analyzer's response factor for NO<sub>2</sub>.

(h) If the NO<sub>2</sub> response factor is less than 0.95 or greater than 1.05, take corrective action by repairing or replacing the analyzer.

(i) Before using a ZrO<sub>2</sub> analyzer for emission testing, demonstrate that the

corrective action resulted in an NO<sub>2</sub> response factor of at least 0.95.

Corrective action may include adding an NO<sub>2</sub> to NO converter to your emission testing system.

(j) You may use a  $\text{NO}_x$  ZrO<sub>2</sub> analyzer that has an NO<sub>2</sub> response factor greater than 1.05 as long as you meet all the following criteria:

(1) You try to correct the problem.

(2) The measurement deficiency does not affect your ability to show that your engines comply with all applicable emission standards.

(k) *Oxygen debt check.* If you use a  $\text{NO}_x$  ZrO<sub>2</sub> analyzer in exhaust that has oxygen, then you do not have to perform this check. However, if you use a  $\text{NO}_x$  ZrO<sub>2</sub> analyzer in exhaust that has no oxygen and some CO and hydrocarbons, then perform this check as follows:

(1) Start, operate, zero, and span the  $\text{NO}_x$  ZrO<sub>2</sub> analyzer according to the instrument manufacturer's instructions using a span gas that contains only NO and a balance gas. The span gas must not contain CO or hydrocarbons.

(2) Select a tri-blend span gas of NO, CO and C<sub>3</sub>H<sub>8</sub> that meets the specifications of § 1065.750, and record the NO concentration.

(3) Introduce the tri-blend span gas at the inlet to the analyzer.

(4) Allow time for the analyzer response to stabilize. Stabilization time may include time to purge the transfer line and to account for analyzer response.

(5) While the analyzer measures the sample's concentration, record its output at its nominal frequency to record 300 data points. Calculate the arithmetic mean of these 300 points.

(l) If the mean calculated in paragraph (k)(5) of this section is not within  $\pm 2\%$  of the tri-blend NO concentration, take corrective action by repairing or replacing the analyzer, or do not use it to measure  $\text{NO}_x$  in exhaust with an oxygen debt (*i.e.*, net fuel-rich exhaust).

(m) Before using a ZrO<sub>2</sub> analyzer for emission testing in exhaust that has an oxygen debt, demonstrate that corrective action resulted in an oxygen debt check that returns a mean in paragraph (k)(5) of this section of at least 98% of the tri-blend NO concentration.

(n) You may use a  $\text{NO}_x$  ZrO<sub>2</sub> analyzer for emission testing in exhaust that has an oxygen debt if the mean in paragraph (k)(5) of this section is greater than 102% of the tri-blend NO concentration as long as you meet all the following criteria:

(1) You try to correct the problem.

(2) The measurement deficiency does not affect your ability to show that your engines comply with all applicable emission standards.

**§ 1065.376 Chiller NO<sub>2</sub> penetration.**

(a) *Scope and frequency.* If you use a chiller to dry a sample upstream of a NO<sub>x</sub> measurement instrument, but you don't use an NO<sub>2</sub> to NO converter upstream of the chiller, you must perform this check. Perform this check after initial installation and after major maintenance.

(b) *Measurement principles.* A chiller removes water, which can otherwise interfere with a NO<sub>x</sub> measurement. However, liquid water in an improperly designed chiller can remove NO<sub>2</sub> from the sample. Therefore, if a chiller is used without an NO<sub>2</sub> to NO converter upstream, it could remove NO<sub>2</sub> from the sample prior to NO<sub>x</sub> measurement.

(c) *System requirements.* An chiller must meet the following performance check so that at least 95% of the total NO<sub>x</sub> is measured at the lowest expected NO/NO<sub>x</sub> fraction.

(d) *Procedure.* Use the following procedure to check the performance of your chiller.

(1) *Instrument setup.* Follow the analyzer and chiller manufacturers' start-up and operation instructions. Adjust the analyzer and chiller as needed to optimize performance.

(2) *Equipment setup.* Connect an ozonator's inlet to a zero air source and connect its outlet to one port of a 3-way tee fitting. Connect an NO span gas to another port of the tee. Connect a heated line at 100 °C to the last port, and connect a heated 3-way tee to the other end of the line. Connect a dewpoint generator set at a dewpoint of 50 °C to one end of a heated line at 100 °C. Connect the other end of the line to the heated tee, and connect a third 100 °C heated line to the chiller inlet. Provide an overflow vent line at the chiller inlet.

(3) For the steps in paragraphs (d)(4) through (7) of this section, set your analyzer to measure only NO (e.g., NO mode), or only read the NO channel of your analyzer.

(4) *Initial NO<sub>x</sub> adjustment.* With the dewpoint generator and the ozonator off, adjust the NO and zero gas flows so that the NO concentration at the analyzer is at 2 times the peak total NO<sub>x</sub> concentration expected during testing. Verify that gas is flowing out of the overflow vent line.

(5) *Total NO<sub>x</sub> adjustment.* Turn on the dewpoint generator and adjust its flow so that the NO concentration at the analyzer is at the peak total NO<sub>x</sub> concentration expected during testing. Verify that gas is flowing out of the overflow vent line.

(6) *NO/NO<sub>x</sub> adjustment.* Turn on the ozonator and adjust the ozonator so that the NO concentration measured by the analyzer decreases to represent the

minimum NO/NO<sub>x</sub> fraction expected during testing. Calculate this fraction as the NO concentration with the ozonator on divided by the NO concentration with the ozonator off. Determine your expected minimum fraction from previous emission tests or estimate it based on good engineering judgment. For example, for a stoichiometric spark-ignition engine, this minimum fraction may be (90 to 95)% NO/NO<sub>x</sub>; for a compression-ignition engine, this minimum fraction may be (65 to 85)% NO/NO<sub>x</sub>. In the case of a compression-ignition engine with an NO<sub>2</sub> storage and reduction aftertreatment system, this ratio may be (0 to 10)% NO/NO<sub>x</sub>.

(7) If you cannot adjust the ozonator to achieve the expected minimum NO/NO<sub>x</sub> fraction, select a higher concentration NO span gas and repeat steps in paragraphs (d)(3) through (6). This will increase the amount of zero air flow to the ozonator. If this solution does not work, you may substitute the zero air with purified O<sub>2</sub>.

(8) *Data collection.* Maintain the ozonator adjustment in paragraph (d)(6) of this section, but turn off power to the ozonator.

(i) Switch the analyzer to measure total NO<sub>x</sub> (NO<sub>x</sub> mode) or measure NO<sub>x</sub> as the sum of your analyzer NO and NO<sub>2</sub> readings.

(ii) Allow for stabilization, accounting for transport delays and instrument response.

(iii) Calculate the mean of 25 samples from the analyzer and record this value as NO<sub>xref</sub>.

(iv) Turn on the ozonator and allow for stabilization, accounting for transport delays and instrument response.

(v) Calculate the mean of 25 samples from the analyzer and record this value as NO<sub>xmeas</sub>.

(vi) Switch the ozonator off.

(vii) Repeat steps in paragraphs

(d)(8)(i) through (vi) to record seven values of NO<sub>xref</sub> and seven values of NO<sub>xmeas</sub>.

(9) *Performance evaluation.* Calculate the means of the NO<sub>xref</sub> and NO<sub>xmeas</sub> values. Divide the mean NO<sub>xmeas</sub> by the mean NO<sub>xref</sub>. If the result is less than 95%, repair or replace the chiller.

**§ 1065.378 NO<sub>2</sub>-to-NO converter conversion check.**

(a) *Scope and frequency.* If you use an analyzer that measures only NO to determine NO<sub>x</sub>, you must use an NO<sub>2</sub> to NO converter upstream of the analyzer. Perform this check after installing the converter and within six months after the last check. This check must be repeated within six months of the check to verify that the catalytic activity of the

NO<sub>2</sub> to NO converter has not deteriorated.

(b) *Measurement principles.* An NO<sub>2</sub> to NO converter allows an analyzer that measures only NO to determine total NO<sub>x</sub> by converting the NO<sub>2</sub> in exhaust to NO.

(c) *System requirements.* An NO<sub>2</sub>-to-NO converter must meet the following performance check so that at least 95% of the total NO<sub>x</sub> is measured at the lowest expected NO/NO<sub>x</sub> fraction.

(d) *Procedure.* Use the following procedure to check the performance of your NO<sub>2</sub> to NO converter.

(1) *Instrument setup.* Follow the analyzer and NO<sub>2</sub> to NO converter manufacturers' start-up and operation instructions. Adjust the analyzer and converter as needed to optimize performance.

(2) *Equipment setup.* Connect an ozonator's inlet to a zero air source and connect its outlet to one port of a 4-way cross fitting. Connect an NO span gas to another port of the cross. Connect the NO<sub>2</sub> to NO converter inlet to another port, and connect an overflow vent line to the last port.

(3) *Total NO<sub>x</sub> adjustment.* With the NO<sub>2</sub> to NO converter in the bypass mode (e.g., NO mode) and the ozonator off, adjust the NO and zero gas flows so that the NO concentration at the analyzer is at the peak total NO<sub>x</sub> concentration expected during testing. Verify that gas is flowing out of the overflow vent.

(4) *NO/NO<sub>x</sub> adjustment.* With the NO<sub>2</sub> to NO converter still in the bypass mode, turn on the ozonator and adjust the ozonator so that the NO concentration measured by the analyzer decreases to represent the minimum NO/NO<sub>x</sub> fraction expected during testing. Calculate this fraction as the NO concentration with the ozonator on divided by the NO concentration with the ozonator off. Determine your expected minimum fraction from previous emission tests or estimate it based on good engineering judgment.

For example, for a stoichiometric spark-ignition engine, this minimum fraction may be (90 to 95)% NO/NO<sub>x</sub>; for a compression-ignition engine, this minimum fraction may be (65 to 85)% NO/NO<sub>x</sub>. In the case of a compression-ignition engine with an NO<sub>2</sub> storage and reduction aftertreatment system, this ratio may be (0 to 10)% NO/NO<sub>x</sub>.

(5) If you cannot adjust the ozonator to achieve the expected minimum NO/NO<sub>x</sub> fraction, select a higher concentration NO span gas and repeat steps in paragraphs (d)(3) and (4). This will increase the amount of zero air flow to the ozonator. If this solution does not

work, you may substitute the zero air with purified O<sub>2</sub>.

(6) *Data collection.* Maintain the ozonator adjustment in paragraph (d)(4) of this section, but turn off power to the ozonator. Switch the NO<sub>2</sub> to NO converter from bypass mode to sample mode (e.g., NO<sub>x</sub> mode) so that the sample flows through the converter to the analyzer.

(i) Allow for stabilization, accounting only for transport delays and instrument response.

(ii) Calculate the mean of 25 samples from the analyzer and record this value as NO<sub>x,ref</sub>.

(iii) Turn on the ozonator and allow for stabilization, accounting only for transport delays and instrument response. Do not allow extra stabilization time to account for NO<sub>2</sub> to NO converter response.

(iv) Calculate the mean of 25 samples from the analyzer and record this value as NO<sub>x,meas</sub>.

(v) Switch the ozonator off.

(vi) Repeat the steps in paragraphs (d)(6)(i) through (v) of this section to record seven values of NO<sub>x,ref</sub> and seven values of NO<sub>x,meas</sub>.

(7) *Performance evaluation.* Calculate the means of the NO<sub>x,ref</sub> and NO<sub>x,meas</sub> values. Divide the mean NO<sub>x,meas</sub> by the mean NO<sub>x,ref</sub>. If the result is less than 95%, repair or replace the NO<sub>2</sub> to NO converter.

## PM Measurements

### § 1065.390 PM balance and weighing process performance check.

(a) *Scope and frequency.* If you measure PM, check the balance performance and the PM weighing environment as described in this section within 12 h before weighing.

(b) *Measurement principles.* You must check balance performance by zeroing and spanning it. Use calibration weights that meet the specifications in § 1065.790 to perform this check. You must also check the PM-weighing environment and weighing process to make sure it has not been compromised by improper balance operation, environmental contamination, or some other problem with the weighing process.

(c) *System requirements.* Zero and span the balance. The reference sample weighing procedure described in paragraph (e) of this section must return a change in the reference samples' mean mass of no more than ±10% of the net PM mass expected at the standard or ±10 µg, whichever is higher, and ±10 mg if the expected PM mass at the standard is not known. For example, a central PM weighing lab might not have

information about an applicable standard, the amount of exhaust dilution, and the amount of exhaust sampled to determine an expected value. If the reference sample weighing procedure exceeds this threshold, invalidate all PM results that were sampled after the last time the reference sample weighing procedure was within these specifications.

(d) *Procedure for checking balance performance.* If you normally use average values by repeating the weighing process to improve the accuracy and precision of PM measurements, use the same process to check balance performance using either of the following procedures. Use an automated procedure to check balance performance if it meets the intent described in paragraph (b) of this section. Otherwise use a manual procedure in which you zero the balance and span the balance with a calibration weight.

(e) *Procedure for checking reference sample weighing procedures.* Check the reference sample weighing procedure as follows:

(1) Keep at least two unused PM sample media in the PM-stabilization environment for use as reference samples. If you collect PM with filters, select unused filters of the same medium and size for use as reference samples. You may periodically replace reference samples, using good engineering judgment.

(2) Stabilize reference samples. Consider reference samples stabilized if they have been in the PM-stabilization environment for a minimum of 30 min, and the PM-stabilization environment has been within the specifications of § 1065.190(c) for at least the preceding 30 min.

(3) Exercise the balance several times with a reference sample. We recommend weighing ten samples without recording values.

(4) Zero and span the balance.

(5) Weigh each of the reference samples and record the arithmetic mean of their masses. We recommend using substitution weighing as described in § 1065.590(h). You may repeat weighing to improve accuracy and precision.

(6) Record the balance environment dewpoint, ambient temperature, and barometric pressure.

(7) Use the recorded ambient conditions to correct results for buoyancy as described in § 1065.690. Record the buoyancy-corrected mean mass of the reference samples.

(8) Quantify the mean mass change of reference samples by subtracting the buoyancy-corrected mean mass from the corresponding value from the last time

you checked PM weighing procedures under this paragraph (e).

(f) If the reference samples' mean mass changes by more than 10% of the net PM mass expected at the standard or by ±10 µg, whichever is greater, invalidate all PM results that were sampled after the last time the reference sample weighing procedure was within this specification. Before using a balance for emission testing, replace reference samples and establish their mean mass.

## Subpart E—Engine Selection, Preparation, and Maintenance

### § 1065.401 Test engine selection.

While all engine configurations within a certified engine family must comply with the applicable standards in the standard-setting part, you need not test each configuration for certification.

(a) Select an engine configuration within the engine family for testing, as follows:

(1) Test the engine that we specify, whether we issue general guidance or give you specific instructions.

(2) If we do not tell you which engine to test, follow any instructions in the standard-setting part.

(3) If we do not tell you which engine to test and the standard-setting part does not include specifications for selecting test engines, use good engineering judgment to select the engine configuration within the engine family that is most likely to exceed an emission standard.

(b) In the absence of other information, the following characteristics are appropriate to consider when selecting the engine to test:

(1) Maximum fueling rates.

(2) Maximum loads.

(3) Maximum in-use speeds.

(4) Highest sales volume.

(c) We may select any engine configuration within the engine family for our testing.

### § 1065.405 Test engine preparation and maintenance.

(a) If you are testing an emission-data engine for certification, make sure it is built to represent production engines.

(b) Run the test engine, with all emission-control systems operating, long enough to stabilize emission levels. If you accumulate 50 h of operation for a spark-ignition engine or 125 h for a compression-ignition engine, you may consider emission levels stable without measurement. If the engine needs more operation to stabilize emission levels, record your reasons and the methods for doing this, and give us these records if

we ask for them. You may also use the provisions of § 1065.10 to request a shorter period of engine operation at which emission levels may be considered stable without measurement.

(c) Do not service the test engine before you stabilize emission levels, unless we approve such maintenance in advance. This prohibition does not apply to your recommended oil and filter changes for newly produced engines, or to idle-speed adjustments.

(d) For accumulating operating hours on your test engines, select engine operation that represents normal in-use operation for the engine family.

(e) If your engine will be used in a vehicle equipped with a canister for storing evaporative hydrocarbons for eventual combustion in the engine, attach a canister fully loaded with fuel vapors before running a test. Connect the canister's purge port to the engine and plug the canister port that is normally connected to the fuel tank. Use a canister and plumbing arrangement that represents the in-use configuration of the largest capacity in all expected applications. You may request to omit using an evaporative canister during testing if you can show that it would not affect your ability to show compliance with the applicable emission standards. You do not have to accumulate engine operation with an installed canister.

**§ 1065.410 Maintenance limits for stabilized test engines.**

(a) After you stabilize the test engine's emission levels, you may do maintenance, other than during emission testing, as the standard-setting part specifies. However, you may not do any maintenance based on emission measurements from the test engine.

(b) Other than critical emission-related maintenance, you specify in your application for certification, you must completely test an engine for emissions before and after doing any maintenance that might affect emissions, unless we waive this requirement.

(c) Unless we approve otherwise in advance, you may not use equipment, instruments, or tools to identify bad engine components unless you specify they should be used for scheduled maintenance on production engines. In this case, if they are not generally available, you must also make them available at dealerships and other service outlets.

(d) You may adjust, repair, disassemble, or replace the test engine only with our approval. We may approve these steps if all the following occur:

(1) Something clearly malfunctions—such as persistent misfire, engine stall, overheating, fluid leaks, or loss of oil pressure—and needs maintenance or repair.

(2) You provide us an opportunity to verify the extent of the malfunction before you do the maintenance.

(e) If we determine that a part failure, system malfunction, or associated repairs have made the engine's emission controls unrepresentative of production engines, you may no longer use it as a test engine. Also, if your test engine has a major mechanical failure that requires you to take it apart, you may no longer use it as a test engine.

**§ 1065.415 Durability demonstration.**

If the standard-setting part requires durability testing, you must accumulate service in a way that represents how you expect the engine to operate in use. You may accumulate service hours using an accelerated schedule, such as through continuous operation.

(a) *Maintenance.* The following limits apply to the maintenance that we allow you to do on a test engine:

(1) You may perform scheduled maintenance that you recommend to operators, but only if it is consistent with the standard-setting part's restrictions.

(2) You may perform additional maintenance only as specified in § 1065.410(b).

(b) *Emission measurements.* Perform emission tests following the provisions of this part and the standard-setting part. Perform emission tests to determine deterioration factors consistent with good engineering judgment. Evenly space any tests between the first and last test points throughout the durability period, unless we approve otherwise.

**Subpart F—Running an Emission Test in the Laboratory**

**§ 1065.501 Overview.**

(a) Use the procedures detailed in this subpart to measure engine emissions in a laboratory by performing the following tasks:

(1) Map your engine by recording specified torque and speed data.

(2) Use your engine map to transform normalized duty cycles into reference duty cycles for your engine.

(3) Prepare your engine, equipment, and measurement instruments for an emission test.

(4) Perform pre-test procedures to verify proper operation of certain equipment and analyzers.

(5) Record pre-test data.

(6) Start or restart the engine and sampling systems.

(7) Sample emissions throughout the duty cycle.

(8) Record post-test data.

(9) Perform post-test procedures to verify proper operation of certain equipment and analyzers.

(b) The general test consists of a duty cycle made of one or more of the following segments (check the standard-setting part for specific duty cycles):

(1) Either a cold-start transient cycle where you measure emissions, or a warm-up cycle where you do not measure emissions. Transient testing consists of a sequence of target values for speed and torque that change continuously throughout the duty cycle.

(2) A hot-start transient test. Some duty cycles may omit engine starting from the "hot-start" cycle.

(3) A steady-state test with a warmed-up engine. Steady-state tests may involve discrete-mode testing or ramped-modal testing. Discrete-mode testing consists of a series of discrete test modes with engine operation stabilized at fixed speeds and torques, with separate emission measurements for each mode. Ramped-modal testing consists of a continuous time trace that includes a series of stable operating modes connected by defined transitions, with a single emission measurement for the whole cycle.

(c) Other subparts in this part identify how to select and prepare an engine for testing (subpart E), perform the required engine service accumulation (subpart E), and calculate emission results (subpart G).

(d) Subpart J of this part describes how to perform field testing.

**§ 1065.510 Engine mapping.**

(a) *Scope and frequency.* An engine map is a data set that consists of a series of paired values for engine speed and maximum brake torque. Map your engine while it is connected to a dynamometer. Use the most recent engine map to transform a normalized duty cycle from the standard-setting part to a reference duty cycle specific to your engine. Normalized duty cycles are specified in the standard-setting part. Map or re-map an engine before a test if any of the following apply:

(1) You have not performed an initial engine map.

(2) The barometric pressure near the engine's air inlet is not within 5% of the barometric pressure recorded at the time of the last engine map.

(3) The engine or emission-control system has undergone changes that might affect maximum torque performance.

(4) You capture an incomplete map on your first attempt or you do not

complete a map within the specified time tolerance. You may repeat mapping as necessary to capture a complete map within the specified time.

(5) You may update an engine map at any time by repeating the engine-mapping procedure.

(b) *Mapping variable-speed engines.*

Map variable-speed engines as follows:

(1) Record the barometric pressure.

(2) Warm up the engine by operating it at any speed and at approximately 75% of the engine's expected maximum power until either the engine coolant's temperature or block absolute temperature is within  $\pm 2\%$  of its mean value for at least 2 min or until the engine thermostat controls engine temperature.

(3) Operate the engine at its warm, no-load idle speed.

(4) Set operator demand to maximum and control engine speed at  $(95 \pm 1)\%$  of its warm, no-load idle speed for at least 15 s. For engines with reference duty cycles whose lowest speed is greater than warm, no-load idle speed, you may start the map at  $(95 \pm 1)\%$  of the lowest reference speed.

(5) Perform one of the following:

(i) For any naturally aspirated engine or for any engine subject only to steady-state duty cycles, you may map it at discrete speeds by selecting at least 20 evenly spaced setpoints between warm, no-load idle and the highest speed above maximum mapped power at which (50 to 75)% of maximum power occurs. At each setpoint, stabilize speed and allow torque to stabilize. Record the average speed and torque at each setpoint. We recommend that you stabilize an engine for at least 15 s at each setpoint and record the average feedback speed and torque of the last (4 to 6) s. Use linear interpolation to determine intermediate speed and torque values.

(ii) For any variable-speed engine, you may map it by using a continuous sweep of speed by continuing to record the mean feedback speed and torque at 1 Hz or more frequently and increasing speed at a constant rate such that it takes (4 to 6) min to sweep from 95% of warm, no-load idle to the highest speed above maximum power at which (50 to 75)% of maximum power occurs. Stop recording after you complete the sweep. From the series of mean speed and maximum torque values, use linear interpolation to determine intermediate values. Use this series of speed and torque values to generate the power map as described in paragraph (e) of this section.

(c) *Negative torque mapping.* If your engine is subject to a reference duty cycle that specifies negative torque

values, generate a motoring map by any of the following procedures:

(1) Multiply the positive torques from your map by  $-40\%$ . Use linear interpolation to determine intermediate values.

(2) Map the amount of negative torque required to motor the engine by repeating paragraph (c) of this section without fuel, or with minimum operator demand if operating without fuel would damage the engine.

(3) Determine the amount of negative torque required to motor the engine at the following two points: at warm, no-load idle and at the highest speed above maximum power at which (50 to 75)% of maximum power occurs. Operate the engine without fuel, or with minimum operator demand if operating without fuel would damage the engine. Use linear interpolation to determine intermediate values.

(d) *Mapping constant-speed engines.* For constant-speed engines, generate a map as follows:

(1) Record the barometric pressure.

(2) Warm up the engine by operating it at any speed and at approximately 75% of the engine's expected maximum power until either the engine coolant's temperature or block absolute temperature is within  $\pm 2\%$  of its mean value for at least 2 min or until the engine thermostat controls engine temperature.

(3) You may operate the engine with a production constant-speed governor or simulate a constant-speed governor by controlling engine speed with an operator demand control system described in § 1065.110. The installed governor may be an isochronous or a speed-droop governor.

(4) With the governor or simulated governor controlling speed via operator demand, operate the engine at no-load governed speed (at high speed, not low idle) for at least 15 s.

(5) Record mean feedback speed and torque at 1 Hz or more frequently and use the dynamometer to increase torque at a constant rate. Unless the standard setting part specifies otherwise, complete the map such that it takes (2 to 4) min to sweep from no-load governed speed to the lowest speed below maximum mapped power at which the engine develops (85–95)% of maximum mapped power. You may map your engine to lower speeds. Stop recording after you complete the sweep. Use this series of speed and torque values to generate the power map as described in paragraph (e) of this section.

(e) *Power mapping.* For all engines, create a power-versus-speed map by transforming torque and speed values to

corresponding power values. Use the mean values from the recorded map data. Do not use any interpolated values. Multiply each torque by its corresponding speed and apply the appropriate conversion factors to arrive at units of power (kW).

(f) *Test speed and test torque.* Transform your duty cycles using maximum test speed for variable-speed engines and maximum test torque for constant-speed engines. You may declare maximum test speed before mapping as long as it is within (97.5 to 102.5)% of its mapped value. You may declare maximum test torque before mapping as long as it is within (95 to 100)% of its mapped value. Otherwise, you must use the measured value for transforming duty cycles.

(g) *Other mapping procedures.* You may use other mapping procedures if you believe the procedures specified in this section are unsafe or unrepresentative for your engine. Any alternate techniques must satisfy the intent of the specified mapping procedures, which is to determine the maximum available torque at all engine speeds that occur during a duty cycle. Report any deviations from this section's mapping procedures.

**§ 1065.512 Duty cycle generation.**

(a) The standard-setting part defines applicable duty cycles in a normalized format. A normalized duty cycle consists of a sequence of paired values for speed and torque or for speed and power.

(b) Transform normalized values of speed, torque, and power using the following conventions:

(1) *Engine speed for variable-speed engines.* For variable-speed engines, normalized speed may be expressed as a percentage between idle speed and maximum test speed,  $f_{\text{ntest}}$ , or speed may be expressed by referring to a defined speed by name, such as "warm, no-load idle," "intermediate speed," or "A," "B," or "C" speed. Section 1065.610 describes how to transform these normalized values into a sequence of reference speeds,  $f_{\text{ref}}$ . Note that the cycle validation criteria in § 1065.514 allow an engine to govern itself at its in-use idle speed. This allowance permits you to test engines with enhanced-idle devices.

(2) *Engine torque for variable-speed engines.* For variable-speed engines, normalized torque is expressed as a percentage of the mapped torque at the corresponding reference speed. Section 1065.610 describes how to transform normalized torques into a sequence of reference torques,  $T_{\text{ref}}$ . Section 1065.610 also describes under what conditions

you may command  $T_{ref}$  greater than the reference torque you calculated from a normalized duty cycle. This provision permits you to command  $T_{ref}$  values representing curb-idle transmission torque (CITT).

(3) *Engine torque speed for constant-speed engines.* For constant-speed engines, normalized torque is expressed as a percentage of maximum test torque,  $T_{test}$ . Section 1065.610 describes how to transform normalized torques into a sequence of reference torques,  $T_{ref}$ . Section 1065.610 also describes under what conditions you may command  $T_{ref}$  greater than 0 Nm when a normalized duty cycle specifies a 0% torque command.

(4) *Engine power.* For all engines, normalized power is expressed as a percentage of mapped power at maximum test speed,  $f_{ntest}$ . Section 1065.610 describes how to transform these normalized values into a sequence of reference powers  $P_{ref}$ . You may convert these reference powers to reference speeds and torques for operator demand and dynamometer control.

(c) *Commands for variable-speed engines.* Command reference speeds and torques sequentially to perform a duty cycle. Update commands and record reference and feedback values at a frequency of at least 5 Hz. Use smooth transitions between reference values.

(d) *Commands for constant-speed engines.* Use dynamometer controls to command reference torques sequentially for performing a duty cycle. Operate the engine with a production constant-speed governor or simulate a constant-speed governor by controlling engine speed with an operator demand control system described in § 1065.110. Update commands and record reference and feedback values at a frequency of at least

5 Hz. Use smooth transitions between reference values.

(e) *Practice cycles.* You may perform practice duty cycles with the test engine to optimize operator demand and dynamometer controls to meet the cycle validation criteria specified in § 1065.514.

**§ 1065.514 Cycle validation criteria.**

This section describes how to determine if a test engine's feedback speeds and torques adequately matched the reference values in a duty cycle. For any data required in this section, use the reference and feedback values that you recorded during a test interval.

(a) *Testing performed by EPA.* Our tests must meet the specifications of paragraph (g) of this section, unless we determine that failing to meet the specifications is related to engine performance rather than shortcomings of the dynamometer or other laboratory equipment.

(b) *Testing performed by manufacturers.* Emission tests that meet the specifications of paragraph (g) of this section satisfy the standard-setting part's requirements for duty cycles. You may ask to use a dynamometer or other laboratory equipment that cannot meet those specifications. We will approve your request as long as using the alternate equipment does not affect your ability to show compliance with the applicable emission standards.

(c) *Time-alignment.* Because time lag between feedback values and the reference values may bias cycle validation results, you may advance or delay the entire sequence of feedback engine speed and torque pairs to synchronize them with the reference sequence.

(d) *Power.* Before omitting any points under paragraph (e) of this section, calculate feedback power,  $P_i$  and reference power,  $P_{refi}$ , and calculate total

work,  $W$  and reference work,  $W_{ref}$ , as described in § 1065.650. Omit any points recorded during engine cranking. Cranking includes any time when an engine starter is engaged and any time when the engine is motored with a dynamometer for the sole purpose of starting the engine. See § 1065.525(a) and (b) for more information about engine cranking.

(e) *Omitting additional points.* In addition to omitting points recorded during cranking, according to paragraph (d) of this section, you may also omit certain points from duty cycle regression statistics, which are also summarized in Table 1 of this section, as follows:

(1) When operator demand is at its minimum you may omit the following points:

(i) Power and torque, if the reference torque is negative (i.e., engine motoring).

(ii) Power and speed, if the reference speed corresponds to an idle command (0%), the reference torque corresponds to a minimum command (0%), and the absolute value of the feedback torque is less than the corresponding reference torque plus 2% of the maximum mapped torque.

(iii) Two out of three of power, torque, and speed if either feedback speed or feedback torque is greater its reference command. You may not omit a point from regression statistics if both feedback speed and torque are greater than their reference commands.

(2) When operator demand is at its maximum, you may omit two out of three of power, torque, and speed if either feedback speed or feedback torque is less than its reference command. You may not omit a point from regression statistics if both feedback speed and torque are less than their reference commands.

TABLE 1 OF § 1065.514.—SUMMARY OF POINT OMISSION CRITERIA FROM DUTY-CYCLE REGRESSION STATISTICS

| When operator demand is at its . . . | you may omit . . .                               | if . . .   |
|--------------------------------------|--|--|
| minimum . . . . .                    | power and torque . . . . .                       | $T_{ref} < 0$ .<br>$f_{nref} = \text{idle (0\%)} \text{ and } T_{ref} = \text{minimum (0\%)} \text{ and } T < T_{ref} \pm 2\% T_{max \text{ mapped}}$ .  |
| minimum . . . . .                    | power and speed . . . . .                        |  |
| minimum . . . . .                    | 2 out of 3 of power, torque, and speed . . . . . | $f_n > f_{nref} \text{ or } T > T_{ref} \text{ but not if } f_n > f_{nref} \text{ and } T > T_{ref}$ .<br>$f_n < f_{nref} \text{ or } T < T_{ref} \text{ but not if } f_n < f_{nref} \text{ and } T < T_{ref}$ . |
| maximum . . . . .                    | 2 out of 3 of power, torque, and speed . . . . . |  |

(f) Use the remaining points to calculate regression statistics described in § 1065.602, as follows:

(1) Slopes for feedback speed,  $a_{1fn}$ , feedback torque,  $a_{1T}$ , and feedback power  $a_{1P}$ .

(2) Intercepts for feedback speed,  $a_{0fn}$ , feedback torque,  $a_{0T}$ , and feedback power  $a_{0P}$ .

(3) Standard estimates of error for feedback speed,  $SE_{fn}$ , feedback torque,  $SE_T$ , and feedback power  $SE_P$ .

(4) Coefficients of determination for feedback speed,  $r^2_{fn}$ , feedback torque,  $r^2_T$ , and feedback power  $r^2_P$ .

(g) *Cycle statistics.* Unless the standard-setting part specifies otherwise, use the following criteria to validate a duty cycle:

(1) For variable-speed engines only, feedback total work must be at or below 105% of reference total work.

(2) For variable-speed engines only, apply all the statistical criteria in Table 2 of this section.

(3) For constant-speed engines, apply the statistical criteria only for torque in the Table 2 of this section.

TABLE 2 OF § 1065.514>.—DEFAULT STATISTICAL CRITERIA FOR VALIDATING DUTY CYCLES

| Parameter  | Speed                                  | Torque                                | Power                                |
|--|--|---------------------------------------|--------------------------------------|
| Slope, $a_1$ .....                               | $0.950 \leq a_1 \leq 1.030$ .....      | $0.830 \leq a_1 \leq 1.030$ .....     | $0.830 \leq a_1 \leq 1.030$          |
| Absolute value of intercept, $\leq a_0 \leq$ ... | $\leq 10\%$ of warm idle .....         | $\leq 2\%$ of maximum mapped torque   | $\leq 2\%$ of maximum mapped power.  |
| Standard error of estimate, SE .....             | $\leq 5\%$ of maximum test speed ..... | $\leq 10\%$ of maximum mapped torque. | $\leq 10\%$ of maximum mapped power. |
| Coefficient of determination, $r^2$ .....        | $\geq 0.970$ .....                     | $\geq 0.850$ .....                    | $\geq 0.910$ .                       |

**§ 1065.520 Pre-test verification procedures and pre-test data collection.**

(a) If your engine must comply with a PM standard, follow the procedures for PM sample preconditioning and tare weighing in § 1065.590.

(b) Unless the standard-setting part specifies different values, verify that ambient conditions before the test are within the following tolerances:

(1) Ambient temperature of (20 to 30) °C.

(2) Barometric pressure of (80.000 to 103.325) kPa and within ±5% of the value recorded at the time of the last engine map.

(3) Dilution air as specified in § 1065.140(b).

(c) You may test engines at any humidity.

(d) You may perform a final calibration of the speed, torque, and proportional-flow control systems, which may include performing practice duty cycles.

(e) You may perform the following recommended procedure to precondition sampling systems:

(1) Start the engine and use good engineering judgment to bring it to 100% torque above its peak-torque speed.

(2) Operate any dilution systems at their expected flow rates. Prevent aqueous condensation in the dilution systems.

(3) Operate any PM sampling systems at their expected flow rates.

(4) Sample PM for at least 10 min using any sample media. You may change sample media during preconditioning. You may discard preconditioning samples without weighing them.

(5) You may purge any gaseous sampling systems during preconditioning.

(6) You may conduct calibrations or performance checks on any idle equipment or analyzers during preconditioning.

(7) Proceed with the test sequence described in § 1065.530(a)(1).

(f) *HC contamination check.* After the last practice or preconditioning cycle

before an emission test, check for contamination in the HC sampling system as follows:

(1) Select the HC analyzer range for measuring the flow-weighted average concentration expected at the HC standard.

(2) Zero the HC analyzer using zero air introduced at the analyzer port.

(3) Span the HC analyzer using span gas introduced at the analyzer port. Span on a carbon number basis of one (1),  $C_1$ . For example, if you use a  $C_3H_8$  span gas of concentration 200  $\mu\text{mol/mol}$ , span the FID to respond with a value of 600  $\mu\text{mol/mol}$ .

(4) Overflow zero air at the HC probe or into a fitting between the HC probe and the transfer line.

(5) Measure the HC concentration in the sampling system, as follows:

(i) For continuous sampling, record the mean HC concentration as overflow zero air flows.

(ii) For batch sampling, fill the sample medium and record its mean HC concentration.

(6) Record this value as the initial HC concentration,  $x_{HC\text{init}}$ , and use it to correct measured values as described in § 1065.660.

(7) If  $x_{HC\text{init}}$  exceeds the greatest of the following values, determine the source of the contamination and take corrective action, such as purging the system or replacing contaminated portions:

(i) 2% of the flow-weighted average concentration expected at the standard or measured during testing, whichever is greater.

(ii) 2  $\mu\text{mol/mol}$ .

(8) If corrective action does not resolve the deficiency, you may request to use the contaminated system as an alternate procedure under § 1065.10.

**§ 1065.525 Engine starting, restarting, and shutdown.**

(a) Start the engine using one of the following methods:

(1) Start the engine as recommended in the owners manual using a production starter motor and a fully charged battery or a power supply.

(2) Use the dynamometer to start the engine. To do this, motor the engine within ± 25% of its typical in-use cranking speed. Accelerate the engine to cranking speed within ± 25% of the time it would take with an in-use engine. Stop cranking within 1 s of starting the engine.

(b) If the engine does not start after 15 s of cranking, stop cranking and determine why the engine failed to start, unless the owners manual or the service-repair manual describes the longer cranking time as normal.

(c) Respond to engine stalling with the following steps:

(1) If the engine stalls during warm-up before emission sampling begins, restart the engine and continue warm-up.

(2) If the engine stalls during preconditioning before emission sampling begins, restart the engine and restart the preconditioning sequence.

(3) If the engine stalls at any other time after emission sampling begins, the test is void.

(d) Shut down the engine according to the manufacturer's specifications.

**§ 1065.530 Emission test sequence.**

(a) Time the start of testing as follows:

(1) Perform one of the following if you precondition sampling systems as described in § 1065.520(d):

(i) For cold-start duty cycles, shut down the engine. Unless the standard-setting part specifies otherwise, you may use forced cooling to stabilize the temperature of the engine and any aftertreatment systems. You may start a cold-start duty cycle when the temperatures of an engine's lubricant, coolant, and aftertreatment systems are between (20 and 30) °C.

(ii) For hot-start emission measurements, shut down the engine. Start a hot-start duty cycle within 20 min of engine shutdown.

(iii) For testing that involves hot-stabilized emission measurements, such as steady-state testing, you may continue to operate the engine at  $f_{\text{test}}$  and 100% torque if that is the first operating point. Otherwise, operate the

engine at warm, no-load idle or the first operating point of the duty cycle. In any case, start the duty cycle within 10 min after you complete the preconditioning procedure.

(2) For all other testing, perform one of the following:

(i) For cold-start duty cycles, start the engine and the duty cycle when the temperatures of an engine's lubricant, coolant, and aftertreatment systems are between (20 and 30) °C. Unless the standard-setting part specifies otherwise, you may use forced cooling to stabilize the temperature of the engine and any aftertreatment system.

(ii) For hot-start emission measurements, first operate the engine at any speed above peak-torque speed and at (65 to 85)% of maximum mapped power until either the engine coolant temperature or block absolute temperature is within 2% of its mean value for at least 2 min or until the engine thermostat controls engine temperature. Shut down the engine. Start the duty cycle within 20 min of engine shutdown.

(iii) For testing that involves hot-stabilized emission measurements, bring the engine either to warm, no-load idle or the first operating point of the duty cycle. Start the test within 10 min of achieving temperature stability. You may determine temperature stability either as the point at which the engine coolant temperature or the block absolute temperature is within 2% of its mean value for at least 2 min, or the point at which the engine thermostat controls engine temperature.

(b) Take the following steps before emission sampling begins:

(1) For batch sampling, connect clean storage media, such as evacuated bags or tare-weighed filters.

(2) Start all measurement instruments according to the instrument manufacturer's instructions.

(3) Start dilution systems, sample pumps, cooling fans, and the data-collection system.

(4) Preheat any heat exchangers in the sampling system.

(5) Allow heated components such as sample lines, filters, and pumps to stabilize at operating temperature.

(6) Perform vacuum-side leak checks as specified in § 1065.345.

(7) Using bypass, adjust the sample flow rates to desired levels.

(8) Zero any integrating devices.

(9) Zero and span all constituent analyzers using NIST-traceable gases that meet the specifications of § 1065.750. Span flame ionization detector analyzers on a carbon number basis of one (1), C<sub>1</sub>. For example, if you use a C<sub>3</sub>H<sub>8</sub> span gas of concentration

200 μmol/mol, span the FID to respond with a value of 600 μmol/mol.

(10) If you correct for dilution air background concentrations of engine exhaust constituents, start measuring and recording background constituent concentrations.

(c) Start testing as follows:

(1) If an engine is already running and warmed up, and starting is not part of the duty cycle, simultaneously start running the duty cycle, sampling exhaust gases, recording data, and integrating measured values.

(2) If engine starting is part of the duty cycle, initiate data logging, sampling of exhaust gases, and integrating measured values before attempting to start the engine. Initiate the duty cycle when the engine starts.

(d) Before the end of the test interval, continue to operate all sampling and dilution systems to allow the sampling system's response time to elapse. Then stop all sampling and recording, including the recording of background samples. Finally, stop any integrating devices and indicate the end of the duty cycle on the data-collection medium.

(e) Shut down the engine if you have completed testing or if it is part of the duty cycle.

(f) If testing involves another duty cycle after a soak period with the engine off, start a timer when the engine shuts down, and repeat the steps in paragraphs (b) through (e) of this section as needed.

(g) Take the following steps after emission sampling is complete:

(1) Place any used PM samples into covered or sealed containers and return them to the PM-stabilization environment. Follow the PM sample post-conditioning and total weighing procedures in § 1065.595.

(2) As soon as practical after the duty cycle is complete, analyze any gaseous batch samples, including background samples.

(3) After quantifying exhaust gases, check drift as follows:

(i) Record the mean analyzer value after stabilizing a zero gas to the analyzer. Stabilization may include time to purge the analyzer of any sample gas, plus any additional time to account for analyzer response.

(ii) Record the mean analyzer value after stabilizing the span gas to the analyzer. Stabilization may include time to purge the analyzer of any sample gas, plus any additional time to account for analyzer response.

(iii) Use these data to validate and correct for drift as described in § 1065.657.

(h) Determine if the test meets the validation criteria in § 1065.514.

#### § 1065.545 Validation of proportional flow control for batch sampling.

For any proportional batch sample such as a bag sample or PM filter sample, demonstrate that proportional sampling was maintained using one of the following:

(a) Record the sample flow rate and the total flow rate at 1 Hz or more frequently. Use this data with the statistical calculations in § 1065.602 to determine the standard error of the estimate, SE, of the sample flow rate versus the total flow rate. For each test interval, demonstrate that SE was less than or equal to 3.5% of the mean sample flow rate. You may omit up to 5% of the data points as outliers to improve SE.

(b) Record the sample flow rate and the total flow rate at 1 Hz or more frequently. For each test interval, demonstrate that each flow rate was constant within ±2.5% of its respective mean or target flow rate.

(c) For critical-flow venturis, record venturi-inlet conditions at 1 Hz or more frequently. Demonstrate that the density at the venturi inlet was constant within ±2.5% of the mean or target density over each test interval. For a CVS critical-flow venturi, you may demonstrate this by showing that the absolute temperature at the venturi inlet was constant within ±4% of the mean or target temperature over each test interval.

(d) For positive-displacement pumps, record pump-inlet conditions at 1 Hz or more frequently. Demonstrate that the density at the pump inlet was constant within ±2.5% of the mean or target density over each test interval. For a CVS pump, you may demonstrate this by showing that the absolute temperature at the pump inlet was constant within ±2% of the mean or target temperature over each test interval.

(e) Using good engineering judgment, demonstrate using an engineering analysis that the proportional-flow control system inherently ensures proportional sampling under all circumstances expected during testing. For example, you use CFVs for sample flow and total flow and their inlet pressures and temperatures are always the same as each others, and they always operate under critical-flow conditions.

#### § 1065.550 Constituent analyzer range validation, drift validation, and drift correction.

(a) Check the results of all analyzers that do not have auto-ranging capability to determine if any results show that an analyzer operated above 100% of its

range. If an analyzer operated above 100% of its range at any time during the test, perform the following steps:

(1) For batch sampling, re-analyze the sample using the nearest analyzer range that results in a maximum instrument response below 100%. Report the result from the lowest range from which the analyzer operates below 100% of its range for the entire test. Report all results.

(2) For continuous sampling, repeat the entire test using the next higher analyzer range. If the analyzer again operates above 100% of its range, repeat the test using the next higher range. Continue to repeat the test until the analyzer operates at less than 100 % of its range for the entire test. Report all results.

(b) Calculate and correct for drift as described in § 1065.657. Drift invalidates a test if the drift correction exceeds  $\pm 4\%$  of the flow-weighted average concentration expected at the standard or measured during a test interval, whichever is greater.

#### **§ 1065.590 PM sample preconditioning and tare weighing.**

Before an emission test, take the following steps to prepare PM samples and equipment for PM measurements:

(a) Make sure the balance and PM-stabilization environments meet the periodic performance checks in § 1065.390.

(b) Visually inspect unused sample media (such as filters) for defects.

(c) To handle PM samples, use electrically grounded tweezers or a grounding strap, as described in § 1065.190.

(d) Place unused sample media in one or more containers that are open to the PM-stabilization environment. If you are using filters, you may place them in the bottom half of a filter cassette.

(e) Stabilize sample media in the PM-stabilization environment. Consider a sample medium stabilized as long as it has been in the PM-stabilization environment for a minimum of 30 min, during which the PM-stabilization environment has been within the specifications of § 1065.190.

(f) Weigh the sample media automatically or manually, as follows:

(1) For automatic weighing, follow the automation system manufacturer's instructions to prepare samples for weighing. This may include placing the samples in a special container.

(2) For manual weighing, use good engineering judgment to determine if substitution weighing is necessary to show that an engine meets the applicable standard. You may follow the substitution weighing procedure in

paragraph (i) of this section, or you may develop your own procedure.

(g) Correct the measured weight for buoyancy as described in § 1065.690. These buoyancy-corrected values are the tare masses of the PM samples.

(h) You may repeat measurements to determine mean masses. Use good engineering judgment to exclude outliers and calculate mean mass values.

(i) Substitution weighing involves measurement of a reference weight before and after each weighing of a PM sample. While substitution weighing requires more measurements, it corrects for a balance's zero-drift and it relies on balance linearity only over a small range. This is advantageous when quantifying net PM masses that are less than 0.1% of the sample medium's mass. However, it may not be advantageous when net PM masses exceed 1% of the sample medium's mass. The following steps are an example of substitution weighing:

(1) Use electrically grounded tweezers or a grounding strap, as described in § 1065.190.

(2) Use a static neutralizer as described in § 1065.190 to minimize static electric charge on any object before it is placed on the balance pan.

(3) Place on the balance pan a calibration weight that has a similar mass to that of the sample medium and meets the specifications for calibration weights in § 1065.790. If you use filters, this mass should be about (80 to 100) mg for typical 47 mm diameter filters.

(4) Record the stable balance reading, then remove the calibration weight.

(5) Weigh an unused sample, record the stable balance reading and record the balance environment's dewpoint, ambient temperature, and barometric pressure.

(6) Reweigh the calibration weight and record the stable balance reading.

(7) Calculate the arithmetic mean of the two calibration-weight readings recorded immediately before and after weighing the unused sample. Subtract that mean value from the unused sample reading, then add the true mass of the calibration weight as stated on the calibration-weight certificate. Record this result.

(8) Repeat the steps in paragraphs (i)(1) through (7) of this section for additional unused sample media.

(j) If you use filters as sample media, load unused filters that have been tare-weighted into filter cassettes and place the loaded cassettes in a covered or sealed container before taking them to the test cell for sampling. We recommend that you keep filter cassettes clean by periodically washing

or wiping them with a compatible solvent. Depending upon your cassette material, ethanol might be an acceptable solvent.

#### **§ 1065.595 PM sample post-conditioning and total weighing.**

(a) Make sure the balance and PM-stabilization environments meet the periodic performance checks in § 1065.390.

(b) In the PM-stabilization environment, remove PM samples from sealed containers. If you use filters, you may remove them from their cassettes before or after stabilization. When you remove a filter from a cassette, separate the top half of the cassette from the bottom half using a cassette separator designed for this purpose.

(c) To handle PM samples, use electrically grounded tweezers or a grounding strap, as described in § 1065.190.

(d) Visually inspect PM samples. If PM ever contacts the transport container, cassette assembly, filter-separator tool, tweezers, static neutralizer, balance, or any other surface, void the measurements associated with that sample and clean the surface it contacted.

(e) To stabilize PM samples, place them in one or more containers that are open to the PM-stabilization environment, which is described in § 1065.190. Consider a sample stabilized as long as it has been in the PM-stabilization environment for a minimum of 30 min, during which the PM-stabilization environment has been within the specifications of § 1065.190. Alternatively, for engines subject to PM standards above 0.05 g/kW-hr, you may consider a sample medium stabilized after 60 min.

(f) Repeat the procedures in § 1065.590(f) through (h) to weigh used PM samples, but refer to a sample's post-test mass after correcting for buoyancy as its total mass.

(g) Subtract each buoyancy-corrected tare mass from its respective buoyancy-corrected total mass. The result is the net PM mass,  $m_{PM}$ . Use  $m_{PM}$  in emission calculations in § 1065.650.

#### **Subpart G—Calculations and Data Requirements**

##### **§ 1065.601 Overview.**

(a) This subpart describes how to use the signals recorded before, during, and after an emission test to calculate brake-specific emissions of each regulated constituent.

(b) You may use data from multiple systems to calculate test results, consistent with good engineering

judgment. We allow weighted averages where appropriate. You may discard statistical outliers, but you must report all results.

(c) Calculations for some calibrations and performance checks are in this subpart.

(d) Statistical values are defined in this subpart.

**§ 1065.602 Statistics.**

(a) This section contains equations and example calculations for statistics that are specified in this part. In this section we use the letter "y" to denote a generic measured quantity, the superscript over-bar "-" to denote an arithmetic mean, and the subscript "ref"

to denote the reference quantity being measured.

(b) *Arithmetic mean.* Calculate an arithmetic mean,  $\bar{y}$  as follows,

$$\bar{y} = \frac{\sum_{i=1}^N y_i}{N}$$

Example:

N=3  
 $\gamma_1 = 10.60$   
 $\gamma_2 = 11.91$   
 $\gamma N = \gamma_3 = 11.20$

$$\bar{y} = \frac{\sum_{i=1}^3 y_i}{3} = \frac{10.60 + 11.91 + 11.09}{3}$$

$\bar{y} = 11.20$

(c) *Standard deviation.* Calculate a non-biased (e.g., N-1) sample standard deviation,  $\sigma$ , as follows:

$$\sigma_y = \sqrt{\frac{\sum_{i=1}^N (y_i - \bar{y})^2}{(N-1)}}$$

Example:

N=3  
 $\gamma_1 = 10.60$   
 $\gamma_2 = 11.91$   
 $\gamma N = \gamma_3 = 11.09$   
 $\bar{\gamma} = 11.20$

$$\sigma_y = \sqrt{\frac{\sum_{i=1}^3 (y_i - 11.2)^2}{3-1}} = \sqrt{\frac{(10.60 - 11.2)^2 + (11.91 - 11.2)^2 + (11.09 - 11.2)^2}{2}}$$

$\sigma_y = 0.6619$

(d) *Root mean square.* Calculate a root mean square,  $rms_y$ , as follows:

$$rms_y = \sqrt{\frac{1}{N} \sum_{i=1}^N y_i^2}$$

Example:

N=3  
 $\gamma_1 = 10.60$   
 $\gamma_2 = 11.91$   
 $\gamma N = \gamma_3 = 11.09$

$$rms_y = \sqrt{\frac{10.60^2 + 11.91^2 + 11.09^2}{3}}$$

$rms_y = 11.21$

(e) *Accuracy.* Calculate an accuracy, as follows, noting that the  $\bar{\gamma}_i$  are arithmetic means, each determined by repeatedly measuring one sample of a single reference quantity,  $\gamma_{ref}$ .

$accuracy = |\gamma_{ref} - \bar{\gamma}|$

Example:

$\gamma_{ref} = 1800.0$   
 (N = 10)

$$\bar{y} = \frac{\sum_{i=1}^{10} \bar{\gamma}_i}{10} = 1802.5$$

accuracy = |1800.0 - 1802.5|  
 accuracy = 2.5

(f) t-test. Determine if your data passes a t-test by using the following equations and tables:

(1) For an unpaired t-test calculate the t statistic and its number of degrees of freedom, v, as follows:

$$t = \frac{|\bar{\gamma}_{ref} - \bar{y}|}{\sqrt{\frac{\sigma_{ref}^2}{N_{ref}} + \frac{\sigma_y^2}{N}}}$$

Example:

$\bar{\gamma}_{ref} = 1205.3$   
 $\bar{\gamma} = 1123.8$   
 $\sigma_{ref} = 9.399$   
 $\sigma_y = 10.583$   
 $N_{ref} = 11$   
 $N = 7$

$$t = \frac{|1205.3 - 1123.8|}{\sqrt{\frac{9.399^2}{11} + \frac{10.583^2}{7}}}$$

t = 16.63

$$v = \frac{\left(\frac{\sigma_{ref}^2}{N_{ref}} + \frac{\sigma_y^2}{N}\right)}{\left(\frac{\sigma_{ref}^2}{N_{ref}} / N_{ref}\right)^2 + \left(\frac{\sigma_{ref}^2}{N}\right)^2}$$

Example:

$\sigma_{ref} = 9.399$   
 $N_{ref} = 11$   
 $\sigma_y = 10.583$   
 $N = 7$

$$v = \frac{\left(\frac{9.399^2}{11} + \frac{10.583^2}{7}\right)^2}{\left(\frac{9.399^2}{11-1}\right)^2 + \left(\frac{10.583^2}{7-1}\right)^2}$$

v = 11.76

(2) For a paired t-test calculate the t statistic and its number of degrees of freedom, v, as follows, noting that the  $\epsilon_i$  are the errors (e.g., differences) between each pair of  $y_{refi}$  and  $y_i$ :

$$t = \frac{|\bar{\epsilon}| \cdot \sqrt{N}}{\sigma_\epsilon}$$

Example:

$\bar{\epsilon} = 0.12580$   
 $N = 16$   
 $\sigma_\epsilon = 0.04837$   
 $\bar{\epsilon} = -0.12580$

$$t = \frac{|-0.12580| \cdot \sqrt{16}}{0.04837}$$

t = 10.403  
 $v = N - 1$   
*Example:*  
 $N = 16$   
 $v = N - 1$   
 $v = 15$

(3) Use Table 1 of this section to compare  $t$  to the  $t_{crit}$  values tabulated versus the number of degrees of freedom. If  $t$  is less than  $t_{crit}$ , then  $t$  passes the  $t$ -test.

TABLE 1 OF § 1065.602-CRITICAL T VALUES VERSUS NUMBER OF DEGREES OF FREEDOM,  $v$

| $t_{crit}$ versus $v$ |            |        |
|-----------------------|------------|--------|
| $v$                   | Confidence |        |
|                       | 90%        | 95%    |
| 1                     | 6.314      | 12.706 |
| 2                     | 2.920      | 4.303  |
| 3                     | 2.353      | 3.182  |
| 4                     | 2.132      | 2.776  |
| 5                     | 2.015      | 2.571  |
| 6                     | 1.943      | 2.447  |
| 7                     | 1.895      | 2.365  |
| 8                     | 1.860      | 2.306  |
| 9                     | 1.833      | 2.262  |
| 10                    | 1.812      | 2.228  |
| 11                    | 1.796      | 2.201  |
| 12                    | 1.782      | 2.179  |
| 13                    | 1.771      | 2.160  |
| 14                    | 1.761      | 2.145  |
| 15                    | 1.753      | 2.131  |
| 16                    | 1.746      | 2.120  |
| 18                    | 1.734      | 2.101  |
| 20                    | 1.725      | 2.086  |

TABLE 1 OF § 1065.602-CRITICAL T VALUES VERSUS NUMBER OF DEGREES OF FREEDOM,  $v$ —Continued

| $t_{crit}$ versus $v$ |            |       |
|-----------------------|------------|-------|
| $v$                   | Confidence |       |
|                       | 90%        | 95%   |
| 22                    | 1.717      | 2.074 |
| 24                    | 1.711      | 2.064 |
| 26                    | 1.706      | 2.056 |
| 28                    | 1.701      | 2.048 |
| 30                    | 1.697      | 2.042 |
| 35                    | 1.69       | 2.03  |
| 40                    | 1.684      | 2.021 |
| 50                    | 1.676      | 2.009 |
| 70                    | 1.667      | 1.994 |
| 100                   | 1.66       | 1.984 |
| INF                   | 1.645      | 1.96  |

(g) *F*-test. Calculate the *F* statistic as follows:

$$F_y = \frac{\sigma_y^2}{\sigma_{ref}^2}$$

Example:

$$\sigma_y = \sqrt{\frac{\sum_{i=1}^N (y_i - \bar{y})^2}{N-1}} = 10.583$$

$$\sigma_{ref} = \sqrt{\frac{\sum_{i=1}^{N_{ref}} (y_{refi} - \bar{y}_{ref})^2}{N_{ref}-1}} = 9.399$$

$$F = \frac{10.583^2}{9.399^2}$$

$F = 1.268$

(1) For a 90% confidence *F*-test, use Table 2 of this section to compare *F* to the  $F_{crit90}$  values tabulated versus  $N$  minus one ( $N - 1$ ) and  $N_{ref}$  minus one ( $N_{ref} - 1$ ). If *F* is less than  $F_{crit90}$ , then *F* passes the *F*-test at 90% confidence.

(2) For a 95% confidence *F*-test, use Table 3 of this section to compare *F* to the  $F_{crit95}$  values tabulated versus  $N$  minus one ( $N - 1$ ) and  $N_{ref}$  minus one ( $N_{ref} - 1$ ). If *F* is less than  $F_{crit95}$ , then *F* passes the *F*-test at 95% confidence.

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Table 2 of §1065.602—Critical  $F$  values,  $F_{crit90}$ , versus  $N-1$  and  $N_{ref}-1$  at 90 % confidence.

| $N-1$       | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    | 12    | 15    | 20    | 24    | 30    | 40    | 60    | 120   | INF   |  |
|-------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--|
| $N_{ref}-1$ |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |  |
| 1           | 39.86 | 49.50 | 53.59 | 55.83 | 57.24 | 58.20 | 58.90 | 59.43 | 59.85 | 60.19 | 60.70 | 61.22 | 61.74 | 62.00 | 62.26 | 62.52 | 62.79 | 63.06 | 63.32 |  |
| 2           | 8.526 | 9.000 | 9.162 | 9.243 | 9.293 | 9.326 | 9.349 | 9.367 | 9.381 | 9.392 | 9.408 | 9.425 | 9.441 | 9.450 | 9.458 | 9.466 | 9.475 | 9.483 | 9.491 |  |
| 3           | 5.538 | 5.462 | 5.391 | 5.343 | 5.309 | 5.285 | 5.266 | 5.252 | 5.240 | 5.230 | 5.216 | 5.200 | 5.184 | 5.176 | 5.168 | 5.160 | 5.151 | 5.143 | 5.134 |  |
| 4           | 4.545 | 4.325 | 4.191 | 4.107 | 4.051 | 4.010 | 3.979 | 3.955 | 3.936 | 3.920 | 3.896 | 3.870 | 3.844 | 3.831 | 3.817 | 3.804 | 3.790 | 3.775 | 3.761 |  |
| 5           | 4.060 | 3.780 | 3.619 | 3.520 | 3.453 | 3.405 | 3.368 | 3.339 | 3.316 | 3.297 | 3.268 | 3.238 | 3.207 | 3.191 | 3.174 | 3.157 | 3.140 | 3.123 | 3.105 |  |
| 6           | 3.776 | 3.463 | 3.289 | 3.181 | 3.108 | 3.055 | 3.014 | 2.983 | 2.958 | 2.937 | 2.905 | 2.871 | 2.836 | 2.818 | 2.800 | 2.781 | 2.762 | 2.742 | 2.722 |  |
| 7           | 3.589 | 3.257 | 3.074 | 2.961 | 2.883 | 2.827 | 2.785 | 2.752 | 2.725 | 2.703 | 2.668 | 2.632 | 2.595 | 2.575 | 2.555 | 2.535 | 2.514 | 2.493 | 2.471 |  |
| 8           | 3.458 | 3.113 | 2.924 | 2.806 | 2.726 | 2.668 | 2.624 | 2.589 | 2.561 | 2.538 | 2.502 | 2.464 | 2.425 | 2.404 | 2.383 | 2.361 | 2.339 | 2.316 | 2.293 |  |
| 9           | 3.360 | 3.006 | 2.813 | 2.693 | 2.611 | 2.551 | 2.505 | 2.469 | 2.440 | 2.416 | 2.379 | 2.340 | 2.298 | 2.277 | 2.255 | 2.232 | 2.208 | 2.184 | 2.159 |  |
| 10          | 3.285 | 2.924 | 2.728 | 2.605 | 2.522 | 2.461 | 2.414 | 2.377 | 2.347 | 2.323 | 2.284 | 2.244 | 2.201 | 2.178 | 2.155 | 2.132 | 2.107 | 2.082 | 2.055 |  |
| 11          | 3.225 | 2.860 | 2.660 | 2.536 | 2.451 | 2.389 | 2.342 | 2.304 | 2.274 | 2.248 | 2.209 | 2.167 | 2.123 | 2.100 | 2.076 | 2.052 | 2.026 | 2.000 | 1.972 |  |
| 12          | 3.177 | 2.807 | 2.606 | 2.480 | 2.394 | 2.331 | 2.283 | 2.245 | 2.214 | 2.188 | 2.147 | 2.105 | 2.060 | 2.036 | 2.011 | 1.986 | 1.960 | 1.932 | 1.904 |  |
| 13          | 3.136 | 2.763 | 2.560 | 2.434 | 2.347 | 2.283 | 2.234 | 2.195 | 2.164 | 2.138 | 2.097 | 2.053 | 2.007 | 1.983 | 1.958 | 1.931 | 1.904 | 1.876 | 1.846 |  |
| 14          | 3.102 | 2.726 | 2.522 | 2.395 | 2.307 | 2.243 | 2.193 | 2.154 | 2.122 | 2.095 | 2.054 | 2.010 | 1.962 | 1.938 | 1.912 | 1.885 | 1.857 | 1.828 | 1.797 |  |
| 15          | 3.073 | 2.695 | 2.490 | 2.361 | 2.273 | 2.208 | 2.158 | 2.119 | 2.086 | 2.059 | 2.017 | 1.972 | 1.924 | 1.899 | 1.873 | 1.845 | 1.817 | 1.787 | 1.755 |  |
| 16          | 3.048 | 2.668 | 2.462 | 2.333 | 2.244 | 2.178 | 2.128 | 2.088 | 2.055 | 2.028 | 1.985 | 1.940 | 1.891 | 1.866 | 1.839 | 1.811 | 1.782 | 1.751 | 1.718 |  |
| 17          | 3.026 | 2.645 | 2.437 | 2.308 | 2.218 | 2.152 | 2.102 | 2.061 | 2.028 | 2.001 | 1.958 | 1.912 | 1.862 | 1.836 | 1.809 | 1.781 | 1.751 | 1.719 | 1.686 |  |
| 18          | 3.007 | 2.624 | 2.416 | 2.286 | 2.196 | 2.130 | 2.079 | 2.038 | 2.005 | 1.977 | 1.933 | 1.887 | 1.837 | 1.810 | 1.783 | 1.754 | 1.723 | 1.691 | 1.657 |  |
| 19          | 2.990 | 2.606 | 2.397 | 2.266 | 2.176 | 2.109 | 2.058 | 2.017 | 1.984 | 1.956 | 1.912 | 1.865 | 1.814 | 1.787 | 1.759 | 1.730 | 1.699 | 1.666 | 1.631 |  |
| 20          | 2.975 | 2.589 | 2.380 | 2.249 | 2.158 | 2.091 | 2.040 | 1.999 | 1.965 | 1.937 | 1.892 | 1.845 | 1.794 | 1.767 | 1.738 | 1.708 | 1.677 | 1.643 | 1.607 |  |
| 21          | 2.961 | 2.575 | 2.365 | 2.233 | 2.142 | 2.075 | 2.023 | 1.982 | 1.948 | 1.920 | 1.875 | 1.827 | 1.776 | 1.748 | 1.719 | 1.689 | 1.657 | 1.623 | 1.586 |  |
| 20          | 2.949 | 2.561 | 2.351 | 2.219 | 2.128 | 2.061 | 2.008 | 1.967 | 1.933 | 1.904 | 1.859 | 1.811 | 1.759 | 1.731 | 1.702 | 1.671 | 1.639 | 1.604 | 1.567 |  |
| 23          | 2.937 | 2.549 | 2.339 | 2.207 | 2.115 | 2.047 | 1.995 | 1.953 | 1.919 | 1.890 | 1.845 | 1.796 | 1.744 | 1.716 | 1.686 | 1.655 | 1.622 | 1.587 | 1.549 |  |
| 24          | 2.927 | 2.538 | 2.327 | 2.195 | 2.103 | 2.035 | 1.983 | 1.941 | 1.906 | 1.877 | 1.832 | 1.783 | 1.730 | 1.702 | 1.672 | 1.641 | 1.607 | 1.571 | 1.533 |  |
| 25          | 2.918 | 2.528 | 2.317 | 2.184 | 2.092 | 2.024 | 1.971 | 1.929 | 1.895 | 1.866 | 1.820 | 1.771 | 1.718 | 1.689 | 1.659 | 1.627 | 1.593 | 1.557 | 1.518 |  |
| 26          | 2.909 | 2.519 | 2.307 | 2.174 | 2.082 | 2.014 | 1.961 | 1.919 | 1.884 | 1.855 | 1.809 | 1.760 | 1.706 | 1.677 | 1.647 | 1.615 | 1.581 | 1.544 | 1.504 |  |
| 27          | 2.901 | 2.511 | 2.299 | 2.165 | 2.073 | 2.005 | 1.952 | 1.909 | 1.874 | 1.845 | 1.799 | 1.749 | 1.695 | 1.666 | 1.636 | 1.603 | 1.569 | 1.531 | 1.491 |  |
| 28          | 2.894 | 2.503 | 2.291 | 2.157 | 2.064 | 1.996 | 1.943 | 1.900 | 1.865 | 1.836 | 1.790 | 1.740 | 1.685 | 1.656 | 1.625 | 1.593 | 1.558 | 1.520 | 1.478 |  |
| 29          | 2.887 | 2.495 | 2.283 | 2.149 | 2.057 | 1.988 | 1.935 | 1.892 | 1.857 | 1.827 | 1.781 | 1.731 | 1.676 | 1.647 | 1.616 | 1.583 | 1.547 | 1.509 | 1.467 |  |
| 30          | 2.881 | 2.489 | 2.276 | 2.142 | 2.049 | 1.980 | 1.927 | 1.884 | 1.849 | 1.819 | 1.773 | 1.722 | 1.667 | 1.638 | 1.606 | 1.573 | 1.538 | 1.499 | 1.456 |  |
| 40          | 2.835 | 2.440 | 2.226 | 2.091 | 1.997 | 1.927 | 1.873 | 1.829 | 1.793 | 1.763 | 1.715 | 1.662 | 1.605 | 1.574 | 1.541 | 1.506 | 1.467 | 1.425 | 1.377 |  |
| 60          | 2.791 | 2.393 | 2.177 | 2.041 | 1.946 | 1.875 | 1.819 | 1.775 | 1.738 | 1.707 | 1.657 | 1.603 | 1.543 | 1.511 | 1.476 | 1.437 | 1.395 | 1.348 | 1.291 |  |
| 120         | 2.748 | 2.347 | 2.130 | 1.992 | 1.896 | 1.824 | 1.767 | 1.722 | 1.684 | 1.652 | 1.601 | 1.545 | 1.482 | 1.447 | 1.409 | 1.368 | 1.320 | 1.265 | 1.193 |  |
| INF         | 2.706 | 2.303 | 2.084 | 1.945 | 1.847 | 1.774 | 1.717 | 1.670 | 1.632 | 1.599 | 1.546 | 1.487 | 1.421 | 1.383 | 1.342 | 1.295 | 1.240 | 1.169 | 1.000 |  |

Table 3 of §1065.602—Critical F values,  $F_{crit(95)}$  versus  $N-1$  and  $N_{ref}-1$  at 95 % confidence

| $N-1$       | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    | 12    | 15    | 20    | 24    | 30    | 40    | 60    | 120   | INF   |
|-------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| $N_{ref}-1$ |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| 1           | 161.4 | 199.5 | 215.7 | 224.5 | 230.1 | 233.9 | 236.7 | 238.8 | 240.5 | 241.8 | 243.9 | 245.9 | 248.0 | 249.0 | 250.1 | 251.1 | 252.2 | 253.2 | 254.3 |
| 2           | 18.51 | 19.00 | 19.16 | 19.24 | 19.29 | 19.33 | 19.35 | 19.37 | 19.38 | 19.39 | 19.41 | 19.42 | 19.44 | 19.45 | 19.46 | 19.47 | 19.47 | 19.48 | 19.49 |
| 3           | 10.12 | 9.552 | 9.277 | 9.117 | 9.014 | 8.941 | 8.887 | 8.845 | 8.812 | 8.786 | 8.745 | 8.703 | 8.660 | 8.639 | 8.617 | 8.594 | 8.572 | 8.549 | 8.526 |
| 4           | 7.709 | 6.944 | 6.591 | 6.388 | 6.256 | 6.163 | 6.094 | 6.041 | 5.999 | 5.964 | 5.912 | 5.858 | 5.803 | 5.774 | 5.746 | 5.717 | 5.688 | 5.658 | 5.628 |
| 5           | 6.608 | 5.786 | 5.410 | 5.192 | 5.050 | 4.950 | 4.876 | 4.818 | 4.773 | 4.735 | 4.678 | 4.619 | 4.558 | 4.527 | 4.496 | 4.464 | 4.431 | 4.399 | 4.365 |
| 6           | 5.987 | 5.143 | 4.757 | 4.534 | 4.387 | 4.284 | 4.207 | 4.147 | 4.099 | 4.060 | 4.000 | 3.938 | 3.874 | 3.842 | 3.808 | 3.774 | 3.740 | 3.705 | 3.669 |
| 7           | 5.591 | 4.737 | 4.347 | 4.120 | 3.972 | 3.866 | 3.787 | 3.726 | 3.677 | 3.637 | 3.575 | 3.511 | 3.445 | 3.411 | 3.376 | 3.340 | 3.304 | 3.267 | 3.230 |
| 8           | 5.318 | 4.459 | 4.066 | 3.838 | 3.688 | 3.581 | 3.501 | 3.438 | 3.388 | 3.347 | 3.284 | 3.218 | 3.150 | 3.115 | 3.079 | 3.043 | 3.005 | 2.967 | 2.928 |
| 9           | 5.117 | 4.257 | 3.863 | 3.633 | 3.482 | 3.374 | 3.293 | 3.230 | 3.179 | 3.137 | 3.073 | 3.006 | 2.937 | 2.901 | 2.864 | 2.826 | 2.787 | 2.748 | 2.707 |
| 10          | 4.965 | 4.103 | 3.708 | 3.478 | 3.326 | 3.217 | 3.136 | 3.072 | 3.020 | 2.978 | 2.913 | 2.845 | 2.774 | 2.737 | 2.700 | 2.661 | 2.621 | 2.580 | 2.538 |
| 11          | 4.844 | 3.982 | 3.587 | 3.357 | 3.204 | 3.095 | 3.012 | 2.948 | 2.896 | 2.854 | 2.788 | 2.719 | 2.646 | 2.609 | 2.571 | 2.531 | 2.490 | 2.448 | 2.405 |
| 12          | 4.747 | 3.885 | 3.490 | 3.259 | 3.106 | 2.996 | 2.913 | 2.849 | 2.796 | 2.753 | 2.687 | 2.617 | 2.544 | 2.506 | 2.466 | 2.426 | 2.384 | 2.341 | 2.296 |
| 13          | 4.667 | 3.806 | 3.411 | 3.179 | 3.025 | 2.915 | 2.832 | 2.767 | 2.714 | 2.671 | 2.604 | 2.533 | 2.459 | 2.420 | 2.380 | 2.339 | 2.297 | 2.252 | 2.206 |
| 14          | 4.600 | 3.739 | 3.344 | 3.112 | 2.958 | 2.848 | 2.764 | 2.699 | 2.646 | 2.602 | 2.534 | 2.463 | 2.388 | 2.349 | 2.308 | 2.266 | 2.223 | 2.178 | 2.131 |
| 15          | 4.543 | 3.682 | 3.287 | 3.056 | 2.901 | 2.791 | 2.707 | 2.641 | 2.588 | 2.544 | 2.475 | 2.403 | 2.328 | 2.288 | 2.247 | 2.204 | 2.160 | 2.114 | 2.066 |
| 16          | 4.494 | 3.634 | 3.239 | 3.007 | 2.852 | 2.741 | 2.657 | 2.591 | 2.538 | 2.494 | 2.425 | 2.352 | 2.276 | 2.235 | 2.194 | 2.151 | 2.106 | 2.059 | 2.010 |
| 17          | 4.451 | 3.592 | 3.197 | 2.965 | 2.810 | 2.699 | 2.614 | 2.548 | 2.494 | 2.450 | 2.381 | 2.308 | 2.230 | 2.190 | 2.148 | 2.104 | 2.058 | 2.011 | 1.960 |
| 18          | 4.414 | 3.555 | 3.160 | 2.928 | 2.773 | 2.661 | 2.577 | 2.510 | 2.456 | 2.412 | 2.342 | 2.269 | 2.191 | 2.150 | 2.107 | 2.063 | 2.017 | 1.968 | 1.917 |
| 19          | 4.381 | 3.522 | 3.127 | 2.895 | 2.740 | 2.628 | 2.544 | 2.477 | 2.423 | 2.378 | 2.308 | 2.234 | 2.156 | 2.114 | 2.071 | 2.026 | 1.980 | 1.930 | 1.878 |
| 20          | 4.351 | 3.493 | 3.098 | 2.866 | 2.711 | 2.599 | 2.514 | 2.447 | 2.393 | 2.348 | 2.278 | 2.203 | 2.124 | 2.083 | 2.039 | 1.994 | 1.946 | 1.896 | 1.843 |
| 21          | 4.325 | 3.467 | 3.073 | 2.840 | 2.685 | 2.573 | 2.488 | 2.421 | 2.366 | 2.321 | 2.250 | 2.176 | 2.096 | 2.054 | 2.010 | 1.965 | 1.917 | 1.866 | 1.812 |
| 22          | 4.301 | 3.443 | 3.049 | 2.817 | 2.661 | 2.549 | 2.464 | 2.397 | 2.342 | 2.297 | 2.226 | 2.151 | 2.071 | 2.028 | 1.984 | 1.938 | 1.889 | 1.838 | 1.783 |
| 23          | 4.279 | 3.422 | 3.028 | 2.796 | 2.640 | 2.528 | 2.442 | 2.375 | 2.320 | 2.275 | 2.204 | 2.128 | 2.048 | 2.005 | 1.961 | 1.914 | 1.865 | 1.813 | 1.757 |
| 24          | 4.260 | 3.403 | 3.009 | 2.776 | 2.621 | 2.508 | 2.423 | 2.355 | 2.300 | 2.255 | 2.183 | 2.108 | 2.027 | 1.984 | 1.939 | 1.892 | 1.842 | 1.790 | 1.733 |
| 25          | 4.242 | 3.385 | 2.991 | 2.759 | 2.603 | 2.490 | 2.405 | 2.337 | 2.282 | 2.237 | 2.165 | 2.089 | 2.008 | 1.964 | 1.919 | 1.872 | 1.822 | 1.768 | 1.711 |
| 26          | 4.225 | 3.369 | 2.975 | 2.743 | 2.587 | 2.474 | 2.388 | 2.321 | 2.266 | 2.220 | 2.148 | 2.072 | 1.990 | 1.946 | 1.901 | 1.853 | 1.803 | 1.749 | 1.691 |
| 27          | 4.210 | 3.354 | 2.960 | 2.728 | 2.572 | 2.459 | 2.373 | 2.305 | 2.250 | 2.204 | 2.132 | 2.056 | 1.974 | 1.930 | 1.884 | 1.836 | 1.785 | 1.731 | 1.672 |
| 28          | 4.196 | 3.340 | 2.947 | 2.714 | 2.558 | 2.445 | 2.359 | 2.291 | 2.236 | 2.190 | 2.118 | 2.041 | 1.959 | 1.915 | 1.869 | 1.820 | 1.769 | 1.714 | 1.654 |
| 29          | 4.183 | 3.328 | 2.934 | 2.701 | 2.545 | 2.432 | 2.346 | 2.278 | 2.223 | 2.177 | 2.105 | 2.028 | 1.945 | 1.901 | 1.854 | 1.806 | 1.754 | 1.698 | 1.638 |
| 30          | 4.171 | 3.316 | 2.922 | 2.690 | 2.534 | 2.421 | 2.334 | 2.266 | 2.211 | 2.165 | 2.092 | 2.015 | 1.932 | 1.887 | 1.841 | 1.792 | 1.740 | 1.684 | 1.622 |
| 40          | 4.085 | 3.232 | 2.839 | 2.606 | 2.450 | 2.336 | 2.249 | 2.180 | 2.124 | 2.077 | 2.004 | 1.925 | 1.839 | 1.793 | 1.744 | 1.693 | 1.637 | 1.577 | 1.509 |
| 60          | 4.001 | 3.150 | 2.758 | 2.525 | 2.368 | 2.254 | 2.167 | 2.097 | 2.040 | 1.993 | 1.917 | 1.836 | 1.748 | 1.700 | 1.649 | 1.594 | 1.534 | 1.467 | 1.389 |
| 120         | 3.920 | 3.072 | 2.680 | 2.447 | 2.290 | 2.175 | 2.087 | 2.016 | 1.959 | 1.911 | 1.834 | 1.751 | 1.659 | 1.608 | 1.554 | 1.495 | 1.429 | 1.352 | 1.254 |
| INF         | 3.842 | 2.996 | 2.605 | 2.372 | 2.214 | 2.099 | 2.010 | 1.938 | 1.880 | 1.831 | 1.752 | 1.666 | 1.571 | 1.517 | 1.459 | 1.394 | 1.318 | 1.221 | 1.000 |

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(h) *Slope.* Calculate a least-squares regression slope, as follows:

$$a_{1y} = \frac{\sum_{i=1}^N (y_i - \bar{y}) \cdot (y_{ref\ i} - \bar{y}_{ref})}{\sum_{i=1}^N (y_{ref\ i} - \bar{y}_{ref})^2}$$

$$a_{1y} = \frac{(2045.8 - 1050.1) \cdot (2045.0 - 1055.3) + \dots + (y_{6000} - 1050.1) \cdot (y_{ref\ 6000} - 1055.3)}{(2045.0 - 1055.3)^2 + \dots + (y_{ref\ 6000} - 1055.3)^2}$$

$$a_{1y} = 1.0110$$

(i) *Intercept.* Calculate a least-squares regression intercept,  $a_{0y}$ , as follows:

$$a_{0y} = \bar{y} - (a_{1y} \cdot \bar{y}_{ref})$$

Example:

$$\bar{y} = 1050.1$$

$$a_{1y} = 1.0110$$

$$\bar{y}_{ref} = 1055.3$$

Example:

$$N = 6000$$

$$y_1 = 2045.8$$

$$y_{ref\ 1} = 2045.0$$

$$\bar{y} = 1050.1$$

$$\bar{y}_{ref} = 1055.3$$

$$a_{0y} = 1050.1 - (1.0110 \cdot 1055.3)$$

$$a_{0y} = -16.8083$$

(j) *Standard estimate of error.* Calculate a standard estimate of error, SE, as follows:

$$SE_y = \sqrt{\frac{\sum_{i=1}^N [y_i - a_{0y} - (a_{1y} \times y_{ref\ i})]^2}{N - 2}}$$

Example:

$$N = 6000$$

$$y_1 = 2045.8$$

$$a_{0y} = 16.8083$$

$$a_{1y} = 1.0110$$

$$y_{ref\ 1} = 2045.0$$

$$SE_y = \sqrt{\frac{[2045.8 - (-16.8083) - (1.0110 \times 2045.0)]^2 + \dots + [y_{6000} - (-16.8083) - (1.0110 \times y_{ref\ 6000})]^2}{6000 - 2}}$$

$$SE_y = 5.348$$

(k) *Coefficient of determination.* Calculate a coefficient of determination,  $r^2$ , as follows:

$$r_y^2 = 1 - \frac{\sum_{i=1}^N [y_i - a_{0y} - (a_{1y} \cdot y_{ref\ i})]^2}{\sum_{i=1}^N [y_i - \bar{y}]^2}$$

$$N = 6000$$

$$y_1 = 2045.8$$

$$a_{0y} = 16.8083$$

$$a_{1y} = 1.0110$$

$$y_{ref\ 1} = 2045.0$$

$$\bar{y} = 1480.5$$

Example:

$$r_y^2 = 1 - \frac{[2045.8 - (-16.8083) - (1.0110 \times 2045.0)]^2 + \dots + [y_{6000} - (-16.8083) - (1.0110 \times y_{ref\ 6000})]^2}{[2045.8 - 1480.5]^2 + \dots + [y_{6000} - 1480.5]^2}$$

$$r_y^2 = 0.9859$$

(1) *Flow weighted average concentration.* A flow-weighted average means the average of a quantity after it is weighted proportional to a corresponding flow rate. For example, if a gas concentration is measured continuously from the raw exhaust of an engine, its flow-weighted average concentration is the sum of the products of each recorded concentration times its respective exhaust flow rate, divided by the number of recorded values. As another example, the bag concentration from a CVS system is the same as the flow-weighted average concentration because the CVS system itself flow-weights the bag concentration. You might already expect a certain flow weighted average concentration of an

emission at its standard based on previous testing with similar engines or testing with similar equipment and instruments. If you need to estimate your expected flow weighted average concentration of an emission at its standard, we recommend using the following examples as a guide for how to estimate the flow weighted average concentration expected at a standard. Note that these examples are not exact and that they contain assumptions that are not always valid. Use good engineering judgement to determine if you can use similar assumptions.

(1) To estimate the flow weighted average raw exhaust  $NO_x$  concentration from a turbo-charged heavy-duty compression-ignition engine at a  $NO_x$  standard of 2.5 g/kWhr, you may do the following:

(i) Based on your engine design, approximate a maximum torque versus speed map and use it with the applicable normalized duty cycle in the standard-setting part to generate a reference duty cycle as described in § 1065.610. Calculate the total reference work,  $W_{ref}$ , as described in § 1065.650. Divide the reference work by the duty cycle's time interval,  $\Delta t_{duty\ cycle}$  to determine average reference power,  $\bar{P}_{ref}$ .

(ii) Based on your engine design, estimate maximum power,  $P_{max}$ , the design speed at maximum power,  $f_{nmax}$ , and the design maximum intake manifold boost pressure,  $P_{inmax}$  and temperature  $T_{inmax}$ . Also estimate an average fraction of power that is lost due to friction and pumping,  $\bar{P}_{frict}$ . Use this information along with the engine displacement volume,  $V_{disp}$ , an

approximate volumetric efficiency,  $\eta_v$ , and the number of engine power strokes per cycle (e.g., 2-stroke or 4-stroke) to

estimate the maximum raw exhaust flow rate,  $\dot{n}_{\text{exhmax}}$ .

(iii) Use your estimated values as described in the following example calculation:

$$\bar{x}_{\text{exp}} = \frac{e_{\text{std}} \cdot W_{\text{ref}}}{M \cdot \dot{n}_{\text{exhmax}} \cdot \Delta t_{\text{duty cycle}} \cdot \left( \frac{\bar{P}_{\text{ref}} + (\bar{P}_{\text{frict}} \cdot P_{\text{max}})}{P_{\text{max}}} \right)}$$

$$\dot{n}_{\text{exhmax}} = \frac{P_{\text{max}} \cdot V_{\text{disp}} \cdot f_{\text{nmax}} \cdot \frac{2}{N_{\text{stroke}}} \cdot \eta_v}{R \cdot T_{\text{max}}}$$

Example:

$e_{\text{NOx}}=2.5 \text{ g/(kW}\cdot\text{hr)}$   
 $W_{\text{ref}}=11.883 \text{ kW}\cdot\text{hr}$   
 $\Delta t_{\text{duty cycle}}=20 \text{ min}$   
 $M_{\text{NOx}}=46.0055 \text{ g/mol}$   
 $\bar{P}_{\text{ref}}=35.65 \text{ kW}$

$P_{\text{max}}=125 \text{ kW}$   
 $\bar{P}_{\text{frict}}=15\%$   
 $\eta_v=0.9$   
 $p_{\text{max}}=300 \text{ kPa}$   
 $V_{\text{disp}}=3.0 \text{ l}$   
 $f_{\text{nmax}}=2800 \text{ rev/min}$   
 $N_{\text{stroke}}=4 \text{ 1/rev}$

$R=8.314472 \text{ J/(mol}\cdot\text{K)}$   
 $T_{\text{max}}=348.15 \text{ K}$   
 $C_p=1000 \text{ Pa/kPa}$   
 $C_v=1000 \text{ l/m}^3$   
 $C_t=60 \text{ s/min}$   
 $C_{\text{mol}}=1000000 \text{ }\mu\text{mol/mol}$

$$\dot{n}_{\text{exhmax}} = \frac{300 \cdot 3.0 \cdot 2800 \cdot \frac{2}{4} \cdot 0.9 \cdot 1000}{8.314472 \cdot 348.15 \cdot 1000 \cdot 60} = 6.53 \text{ mol/s}$$

$$\bar{x}_{\text{exp}} = \frac{2.5 \cdot 11.883}{46.0055 \cdot 6.53 \cdot 20 \cdot 60 \cdot \left( \frac{35.65 + (0.15 \cdot 125)}{125} \right)} \cdot 1000000$$

$\bar{x}_{\text{exp}} = 189.4 \text{ }\mu\text{mol/mol}$

(2) To estimate the flow weighted average NMHC concentration in a CVS from a naturally aspirated nonroad spark-ignition engine at an NMHC standard of 0.5 g/kW-hr, you may do the following:

(i) Based on your engine design, approximate a maximum torque versus speed map and use it with the applicable normalized duty cycle in the standard-setting part to generate a

reference duty cycle as described in § 1065.610. Calculate the total reference work,  $W_{\text{ref}}$ , as described in § 1065.650.

(ii) Multiply your CVS total flow rate by the time interval of the duty cycle,  $\Delta t_{\text{duty cycle}}$ . The result is the total diluted exhaust flow of the  $n_{\text{dexh}}$ .

(iii) Use your estimated values as described in the following example calculation:

$$\bar{x}_{\text{NMHC}} = \frac{e_{\text{std}} \cdot W_{\text{ref}}}{M \cdot \dot{n}_{\text{dexh}} \cdot \Delta t_{\text{duty cycle}}}$$

Example:

$e_{\text{NMHC}}=1.5 \text{ g/(kW}\cdot\text{hr)}$   
 $W_{\text{ref}}=5.389 \text{ kW}\cdot\text{hr}$   
 $M_{\text{NMHC}}=13.875389 \text{ g/mol}$

$\dot{n}_{\text{dexh}}=6.021 \text{ mol/s}$   
 $\Delta t_{\text{duty cycle}}=30 \text{ min}$   
 $C_t=60 \text{ s/min}$   
 $C_{\text{mol}}=1000000 \text{ }\mu\text{mol/mol}$

$$\bar{x}_{\text{NMHC}} = \frac{1.5 \cdot 5.389}{13.875389 \cdot 6.021 \cdot 30 \cdot 60} \cdot 1000000$$

$\bar{x}_{\text{NMHC}} = 53.8 \text{ }\mu\text{mol/mol}$

#### § 1065.605 Field test system overall performance check.

(a) This section contains equations and example calculations for statistics that are specified in § 1065.920 for field-testing systems. In this section we use

the letter "e" to denote the brake-specific emissions of a test interval, the superscript over-bar "-" to denote an arithmetic mean, the subscript "lab" to denote a laboratory result, and the subscript "field" to denote a field-testing result.

(b) Assume that the brake-specific data in the following table was collected by performing the overall field test system check as described in § 1065.920.

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Table 1 of §1065.605—Example of data set from a field test system overall check

| Duty cycle repeats             | Test intervals (e.g. NTE events) |       |       |       |       |      |       |       |       |       |
|--------------------------------|----------------------------------|-------|-------|-------|-------|------|-------|-------|-------|-------|
|                                | 1                                | 2     | 3     | 4     | 5     | 6    | 7     | 8     | 9     | 10    |
| 1 <sub>field</sub>             | 2.00                             | 4.00  | 1.90  | 2.80  | 3.20  | 2.60 | 1.60  | 2.40  | 3.20  | 3.60  |
| 1 <sub>lab</sub>               | 1.90                             | 3.60  | 2.00  | 2.70  | 3.00  | 2.50 | 1.50  | 2.30  | 3.00  | 3.40  |
| 2 <sub>field</sub>             | 2.10                             | 3.40  | 1.80  | 2.50  | 3.40  | 2.50 | 1.80  | 2.20  | 3.00  | 3.40  |
| 2 <sub>lab</sub>               | 2.00                             | 3.80  | 1.90  | 2.70  | 3.20  | 2.60 | 1.70  | 2.10  | 3.40  | 3.20  |
| 3 <sub>field</sub>             | 2.30                             | 3.20  | 1.50  | 2.20  | 3.10  | 2.40 | 1.50  | 1.90  | 3.50  | 3.20  |
| 3 <sub>lab</sub>               | 2.20                             | 3.50  | 1.90  | 2.70  | 3.20  | 2.70 | 1.40  | 2.00  | 3.30  | 3.10  |
| 4 <sub>field</sub>             | 2.40                             | 3.30  | 2.10  | 2.80  | 3.30  | 3.00 | 1.40  | 2.10  | 3.10  | 3.20  |
| 4 <sub>lab</sub>               | 2.30                             | 3.30  | 2.20  | 2.50  | 3.30  | 2.90 | 1.30  | 2.00  | 3.40  | 3.10  |
| 5 <sub>field</sub>             | 2.20                             | 3.10  | 1.90  | 2.50  | 3.60  | 3.50 | 1.30  | 2.00  | 3.20  | 3.00  |
| 5 <sub>lab</sub>               | 2.10                             | 3.20  | 2.10  | 2.40  | 3.20  | 3.30 | 1.30  | 1.80  | 3.30  | 3.30  |
| 6 <sub>field</sub>             | 2.00                             | 3.50  | 1.90  | 2.40  | 3.40  | 2.90 | 1.50  | 2.10  | 3.00  | 3.00  |
| 6 <sub>lab</sub>               | 1.90                             | 3.40  | 1.80  | 2.20  | 3.40  | 2.50 | 1.40  | 2.10  | 3.40  | 3.10  |
| 7 <sub>field</sub>             | 2.20                             | 3.50  | 2.20  | 2.70  | 3.00  | 3.00 | 1.50  | 2.20  | 3.50  | 2.90  |
| 7 <sub>lab</sub>               | 2.10                             | 3.70  | 2.00  | 2.50  | 3.40  | 3.10 | 1.60  | 2.10  | 3.30  | 3.40  |
| Calculations                   |                                  |       |       |       |       |      |       |       |       |       |
| $\bar{e}_{field}$              | 2.17                             | 3.43  | 1.90  | 2.56  | 3.29  | 2.84 | 1.51  | 2.13  | 3.21  | 3.19  |
| $\bar{e}_{lab}$                | 2.07                             | 3.50  | 1.99  | 2.53  | 3.24  | 2.80 | 1.46  | 2.06  | 3.30  | 3.23  |
| $\Delta\bar{e} / e_{lab\ std}$ | 4.0%                             | -2.9% | -3.4% | 1.1%  | 1.7%  | 1.7% | 2.3%  | 2.9%  | -3.4% | -1.7% |
| $UCL_{field}$                  | 2.35                             | 3.81  | 2.23  | 2.85  | 3.51  | 3.42 | 1.74  | 2.33  | 3.46  | 3.50  |
| $UCL_{lab}$                    | 2.37                             | 3.93  | 2.25  | 2.91  | 3.52  | 3.42 | 1.76  | 2.36  | 3.58  | 3.50  |
| $\Delta_{UCL}$                 | -0.02                            | -0.12 | -0.02 | -0.05 | -0.01 | 0.00 | -0.02 | -0.03 | -0.13 | -0.01 |

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(c) For example, calculate for the first test interval  $\bar{e}_{field\ 1}$ ,  $\bar{e}_{lab\ 1}$ , and  $\Delta\bar{e}_1 / e_{lab\ std}$ , and as follows:

$$\bar{e}_{field\ i} = \frac{\sum_{i=1}^N e_{field\ i}}{N} \quad N = 7$$

$$\bar{e}_{field\ 1} = \frac{2.00 + 2.10 + 2.30 + 2.40 + 2.20 + 2.00 + 2.20}{7}$$

$\bar{e}_{field\ 1} = 2.17 \text{ g/kW} \cdot \text{hr}$

similarly,

$$\bar{e}_{lab\ 1} = \frac{1.90 + 2.00 + 2.20 + 2.30 + 2.10 + 1.90 + 2.10}{7}$$

$\bar{e}_{lab\ 1} = 2.07 \text{ g/kW} \cdot \text{hr}$

$\Delta\bar{e}_1 / e_{lab\ std} = (\bar{e}_{field\ 1} - \bar{e}_{lab\ 1}) / e_{lab\ std}$

$e_{lab\ std} = 2.50 \text{ g/kW} \cdot \text{hr}$

$\Delta\bar{e}_1 / e_{lab\ std} = (2.17 - 2.07) / 2.50$

$\Delta\bar{e}_1 / e_{lab\ std} = 4.0\%$

(d) For example, calculate for the second test interval  $UCL_{field\ 2}$ ,  $UCL_{lab\ 2}$ ,  $\Delta_{UCL\ 2}$  as follows:

$UCL_{field\ 2} = \bar{e}_{field\ 2} + 2 \cdot \sigma_{e\ field\ 2}$

see 1065.602(c) for  $\sigma_{e\ field\ 2}$ .

For UCL, recalculate  $\bar{e}_{field\ 2}$  and  $\sigma_{e\ field\ 2}$  after applying measurement allowance.

Example:

measurement allowance = 0.95

$UCL_{field\ 2} = 3.258 + 2 \cdot 0.278$

UCL<sub>field 2</sub> = 3.81 g / kW•hr

similarly,

UCL<sub>lab 2</sub> = 3.500 + 2•0.216

UCL<sub>lab 2</sub> = 3.93 g / kW•hr

ΔUCL<sub>2</sub> = UCL<sub>field 2</sub> - UCL<sub>lab 2</sub>

ΔUCL<sub>2</sub> = 3.81 - 3.93

ΔUCL<sub>2</sub> = -0.12 g / kW•hr

#### § 1065.610 Test cycle generation.

(a) *Maximum test speed,  $f_{ntest}$  and maximum test torque  $T_{test}$ .* For all

engines, calculate test speed from the power versus speed map generated as per § 1065.510.

(1) Based on the power versus speed map, determine the maximum power and the speed at which maximum power occurred. Divide each recorded power by the maximum power and divide each recorded speed by the speed at which maximum power occurred. The resulting data set is a normalized

data set of power versus speed. Use this data set to determine test speed. Test speed is the speed at which the normalized data set returns a maximum value of the sum of the squares of normalized speed and normalized power.

(2) For example:

$$f_{ntest} = f_{n@P_{max}} \cdot \left[ f_{nnormi} @ \max_{i=1}^N (f_{nnormi}^2 + P_{normi}^2) \right]$$

Example:

$f_{n@P_{max}} = 2355$  rev/min

$f_{norm1} = 1.002$ ,  $P_{norm1} = 0.978$

$f_{norm2} = 1.004$ ,  $P_{norm2} = 0.977$

$f_{norm3} = 1.006$ ,  $P_{norm3} = 0.974$

$$(f_{norm1}^2 + P_{norm1}^2) = (1.002^2 + 0.978^2) = 1.960$$

$$(f_{norm2}^2 + P_{norm2}^2) = (1.004^2 + 0.977^2) = 1.963$$

$$(f_{norm3}^2 + P_{norm3}^2) = (1.006^2 + 0.974^2) = 1.961$$

max = 1.963 @  $i = 2$

$f_{ntest} = 2355 \cdot [1.004] = 2364$  rev/min

(3) For variable-speed engines, use this measured test speed—or your declared test speed as described in § 1065.510—to transform normalized speeds to reference speeds as described in paragraph (b) of this section.

(4) For constant-speed engines, use the torque corresponding to this measured test speed as measured test torque—or your declared test torque as described in § 1065.510—to transform normalized torques to reference torques as described in paragraph (c) of this section.

(b) *Speed.* Transform normalized speed values to reference values as follows:

(1) % speed. If your normalized duty cycle specifies % speed values, use your declared warm no-load idle speed and your test speed to transform the duty cycle, as follows:

$$f_{nref} = \% \text{ speed} \cdot (f_{ntest} - f_{nidle}) + f_{nidle}$$

Example:

% speed = 85%

$f_{ntest} = 2364$  rev/min

$f_{nidle} = 650$  rev/min

$f_{nref} = 85\% \cdot (2364 - 650) + 650$

$f_{nref} = 2107$  rev/min

(2) A, B, and C speeds. If your normalized duty cycle specifies speed values as A, B, or C values, use your power versus speed curve to determine the lowest speed below maximum power at which 50% of maximum power occurs. Denote this value as  $n_{10}$ .

Also determine the highest speed above maximum power at which 70% of maximum power occurs. Denote this value as  $n_{hi}$ . Use  $n_{hi}$  and  $n_{10}$  to calculate reference values for A, B, or C speeds as follows:

$$f_{nrefA} = 0.25 \cdot (n_{hi} - n_{10}) + n_{10}$$

$$f_{nrefB} = 0.50 \cdot (n_{hi} - n_{10}) + n_{10}$$

$$f_{nrefC} = 0.75 \cdot (n_{hi} - n_{10}) + n_{10}$$

Example:

$n_{10} = 1005$  rev/min

$n_{hi} = 2385$  rev/min

$$f_{nrefA} = 0.25 \cdot (2385 - 1005) + 1005$$

$$f_{nrefB} = 0.50 \cdot (2385 - 1005) + 1005$$

$$f_{nrefC} = 0.75 \cdot (2385 - 1005) + 1005$$

$f_{nrefA} = 1350$  rev/min

$f_{nrefB} = 1695$  rev/min

$f_{nrefC} = 2040$  rev/min

(3) *Intermediate speed.* If your normalized duty cycle specifies a speed as “intermediate speed”, use your torque versus speed curve to determine the speed at which maximum torque occurs.

(i) Determine the speed at which peak torque occurs. This is peak torque speed.

(ii) If peak torque speed is between (60 to 75) % of test speed, then your reference intermediate speed is peak torque speed.

(iii) If peak torque speed is less than 60% of test speed, then your reference intermediate speed is 60% of test speed.

(iv) If peak torque speed is greater than 75% of test speed, then your reference intermediate speed is 75% of test speed.

(c) *Torque.* Transform normalized torque values to reference values using your maximum torque versus speed map. For variable-speed engines you must first transform normalized speed values into reference speed values. For constant-speed engines, you need only your test torque value.

(1) % torque for variable-speed engines. For a given speed point, multiply the corresponding % torque by the maximum torque at that speed, according to your map. Linearly interpolate mapped torque values to determine torque between mapped speeds. The result is the reference torque for that speed point.

(2) % torque for constant-speed engines. Multiply a % torque value by your test torque. The result is the reference torque for that point.

(3) *Permissible deviations for any engine.* If your engine does not operate in-use below a certain torque under certain conditions, you may use a declared minimum torque as the reference value instead of the value calculated in paragraph (c)(1) or (2) of this section. For example, if your engine is connected to an automatic transmission, it may have a minimum torque called curb idle transmission torque (CITT). In this case, at idle conditions (i.e., 0% speed, 0% torque), you may use CITT as a reference value instead of 0 N•m.

(d) *Power.* Transform normalized power values to reference speed and

torque values using your maximum power versus speed map. For variable-speed engines you must first transform normalized speed values into reference speed values. For constant-speed engines, you need only your maximum power value.

(1) *% power for variable-speed engines.* For a given speed point, multiply the corresponding % power by the maximum power of your entire map. The result is the reference power for that speed point. You may calculate a corresponding reference torque for that point and command that reference torque instead of a reference power.

(2) *% torque for constant-speed engines.* Multiply a % power value by the maximum power of your entire map. The result is the reference power for that point. You may calculate a corresponding reference torque for that point and command that reference torque instead of a reference power.

(3) *Permissible deviations for any engine.* If your engine does not operate in-use below a certain power under

certain conditions, you may use a declared minimum power as the reference value instead of the value calculated in paragraph (d)(1) or (2) of this section. For example, if your engine is directly connected to a propeller, it may have a minimum power called idle power. In this case, at idle conditions (i.e., 0% speed, 0% torque), you may use a corresponding idle torque as a reference torque instead of 0 N·m.

#### § 1065.630 1980 International Gravity Formula.

Calculate the acceleration of Earth's gravity at your latitude, as follows:

$$a_g = 9.7803267715 \times (1 + 5.2790414E-03 \times \sin(\theta)^2 + 2.32718E-05 \times \sin(\theta)^4 + 1.262E-07 \times \sin(\theta)^6 + 7E-10 \times \sin(\theta)^8)$$

Example:

$$\theta = 45^\circ \\ a_g = 9.7803267715 \times (1 + 5.2790414E-03 \times \sin(45)^2 + 2.32718E-05 \times \sin(45)^4 + 1.262E-07 \times \sin(45)^6 + 7E-10 \times \sin(45)^8)$$

$$a_g = 9.8178291229 \text{ m/s}^2$$

#### § 1065.640 PDP and venturi (SSV and CFV) calibration calculations.

(a) *Reference meter conversions.* The following calibration equations use molar flow rate,  $\dot{n}_{ref}$  as a reference quantity. If your reference meter outputs a flow rate in a different quantity such as standard volume rate,  $\dot{V}_{stdref}$  actual volume rate,  $\dot{V}_{actref}$  or mass rate,  $\dot{m}_{ref}$ , convert your reference meter output to molar flow rate using the following:

$$\dot{n}_{ref} = \frac{\dot{V}_{stdref} \cdot P_{std}}{T_{std} \cdot R} = \frac{\dot{V}_{actref} \cdot P_{act}}{T_{act} \cdot R} = \frac{\dot{m}_{ref}}{M_{mix}}$$

Examples:

$$\begin{aligned} \dot{V}_{stdref} &= 1000.00 \text{ ft}^3/\text{min} \\ P_{std} &= 29.9213 \text{ in Hg @ } 32^\circ\text{F} \\ T_{std} &= 68.0^\circ\text{F} \\ R &= 8.314472 \text{ J/(mol}\cdot\text{K)} \\ C_p &= 3386.38 \text{ Pa/in Hg @ } 32^\circ\text{F} \\ C_T &= (T + 459.67)/1.8 \text{ K/}^\circ\text{F} \\ C_V &= 35.314662 \text{ ft}^3/\text{m}^3 \\ C_t &= 60 \text{ s/min} \end{aligned}$$

$$\dot{n}_{ref} = \frac{1000.00 \cdot 29.9213 \cdot 3386.38}{[(68.0 + 459.67)/1.8] \cdot 8.314472 \cdot 35.314662 \cdot 60} = 19.619 \text{ mol/s}$$

$$\begin{aligned} \dot{m}_{ref} &= 17.2683 \text{ kg/mih} \\ M_{mix} &= 28.7805 \text{ g/mol} \\ C_m &= 1000 \text{ g/kg} \end{aligned}$$

$$\dot{n}_{ref} = \frac{17.2683 \cdot 1000}{28.7805 \cdot 60} = 10.000 \text{ mol/s}$$

(b) *PDP calibration calculations.* For each restrictor position, calculate the following values, from the mean values determined in § 1065.340, as follows:

(1) PDP volume pumped per revolution,  $V_{rev}$  m<sup>3</sup>/rev:

$$V_{rev} = \frac{\dot{n}_{ref} \cdot R \cdot \bar{T}_{in}}{\bar{P}_{in} \cdot \bar{f}_{PDP}}$$

Example:

$$\begin{aligned} \dot{n}_{ref} &= 25.096 \text{ mol/s} \\ R &= 8.314472 \text{ J/mol}\cdot\text{K} \\ \bar{T}_{in} &= 299.5 \text{ K} \\ \bar{P}_{in} &= 98.290 \text{ kPa} \\ \bar{f}_{PDP} &= 1205.1 \text{ rev/min} \\ C_t &= 60 \text{ s/min} \\ C_p &= 1000 \text{ (J/m}^3\text{)/kPa} \end{aligned}$$

$$V_{rev} = \frac{60 \cdot 25.096 \cdot 8.314472 \cdot 299.5}{1000 \cdot 98.290 \cdot 1205.1}$$

$$V_{rev} = 0.03166 \text{ m}^3/\text{rev}$$

(2) PDP slip correction factor,  $K_s$  s/rev:

$$K_s = \frac{1}{\bar{f}_{PDP}} \cdot \sqrt{\frac{\bar{P}_{out} - \bar{P}_{in}}{\bar{P}_{out}}}$$

Example:

$$\begin{aligned} \bar{f}_{PDP} &= 1205.1 \text{ rev/min} \\ \bar{P}_{out} &= 100.103 \text{ kPa} \\ \bar{P}_{in} &= 98.290 \text{ kPa} \\ C_t &= 60 \text{ s/min} \end{aligned}$$

$$K_s = \frac{60 \cdot 1}{1205.1} \cdot \sqrt{\frac{100.103 - 98.290}{100.103}}$$

$$K_s = 0.006700 \text{ s/rev}$$

(3) Perform a least-squares regression of PDP volume pumped per revolution,  $V_{rev}$  versus PDP slip correction factor,  $K_s$ , by calculating slope,  $a_1$  and intercept  $a_0$  as described in § 1065.602.

(4) Repeat the procedure in paragraphs (a)(1) through (3) of this section for every speed that you run your PDP.

(5) Use the slopes and intercepts to calculate flow rate during emission testing as described in § 1065.642.

(c) *Venturi governing equations and allowable assumptions.* Because a subsonic venturi (SSV) and a critical-flow venturi (CFV) both operate similarly, their governing equations are the same, except for the equation describing their pressure ratio  $r$  (i.e.,  $r_{SSV}$  versus  $r_{CFV}$ ). The following symbols

are used for the following quantities in subsequent calculations:

$A_t$  = venturi throat cross-sectional area

$C_d$  = discharge coefficient

$C_f$  = flow coefficient

$C_m$  = mass conversion factor

$C_p$  = pressure conversion factor

$d_t$  = venturi throat diameter

$M_{mix}$  = molar mass of gas mixture

$\dot{n}$  = molar flow rate

$p_{in}$  = venturi inlet absolute static pressure

$r$  = pressure ratio

$T_{in}$  = venturi inlet absolute temperature

$Z$  = compressibility factor

$\beta$  = ratio of venturi throat to inlet diameters

$\Delta p$  = differential static pressure; venturi inlet minus venturi throat

$\gamma$  = ratio of specific heats of gas mixture

$$\dot{n} = C_d \cdot C_f \cdot \frac{A_t \cdot p_{in}}{\sqrt{Z \cdot M_{mix} \cdot R \cdot T_{in}}}$$

$$C_f = \left[ \frac{2 \cdot \gamma \cdot \left( 1 - r \frac{\gamma-1}{\gamma} \right)}{(\gamma-1) \cdot \left( r \frac{-2}{\gamma} - \beta^4 \right)} \right]^{\frac{1}{2}}$$

$$r_{SSV} = 1 - \frac{\Delta p}{P_{in}}$$

$$r_{CFV} \frac{1-\gamma}{\gamma} + \left( \frac{\gamma-1}{2} \right) \cdot \beta^4 \cdot r_{CFV}^2 = \frac{\gamma+1}{2}$$

(1) You may iterate to solve for  $r_{CFV}$  and subsequently calculate  $C_f$  for a CFV,  $C_{rCFV}$ , or you may determine  $C_{rCFV}$  from Table 1 of § 1065.640, based on your  $\beta$  and  $\gamma$ .

TABLE 1 OF § 1065.640.— $C_{rCFV}$  VERSUS  $\beta$  AND  $\gamma$

| $\beta$ | $C_{rCFV}$             |  |
|---------|------------------------|--|
|         | $\gamma_{exh} = 1.385$ | $\gamma_{dexh} = \gamma_{air} = 1.399$ |
| 0.000   | 0.6822                 | 0.6846                                 |
| 0.400   | 0.6857                 | 0.6881                                 |
| 0.500   | 0.6910                 | 0.6934                                 |
| 0.550   | 0.6953                 | 0.6977                                 |
| 0.600   | 0.7011                 | 0.7036                                 |
| 0.625   | 0.7047                 | 0.7072                                 |
| 0.650   | 0.7089                 | 0.7114                                 |
| 0.675   | 0.7137                 | 0.7163                                 |
| 0.700   | 0.7193                 | 0.7219                                 |
| 0.720   | 0.7245                 | 0.7271                                 |
| 0.740   | 0.7303                 | 0.7329                                 |
| 0.760   | 0.7368                 | 0.7395                                 |
| 0.770   | 0.7404                 | 0.7431                                 |
| 0.780   | 0.7442                 | 0.7470                                 |
| 0.790   | 0.7483                 | 0.7511                                 |
| 0.800   | 0.7527                 | 0.7555                                 |
| 0.810   | 0.7573                 | 0.7602                                 |
| 0.820   | 0.7624                 | 0.7652                                 |
| 0.830   | 0.7677                 | 0.7707                                 |
| 0.840   | 0.7735                 | 0.7765                                 |
| 0.850   | 0.7798                 | 0.7828                                 |

(2) *Permissible assumptions.* You may make several simplifying assumptions of the governing equations.

(i) For emission testing over the full ranges of raw exhaust, diluted exhaust and dilution air, you may assume that the gas mixture behaves as an ideal gas:  $Z = 1$ .

(ii) For the full range of raw exhaust you may assume a constant ratio of specific heats of  $\gamma = 1.385$ .

(iii) For the full range of diluted exhaust and air (e.g., calibration air or dilution air), you may assume a constant ratio of specific heats of  $\gamma = 1.399$ .

(iv) For the full range of diluted exhaust and air, you may assume the molar mass of the mixture is a function only of the amount of water in the dilution air or calibration air,  $x_{H2O}$ , determined as described in § 1065.645, as follows:

$$M_{mix} = M_{air} \cdot (1 - x_{H2O}) + M_{H2O} \cdot x_{H2O}$$

Example:

$M_{air} = 28.96559 \text{ g/mol}$   
 $x_{H2O} = 0.0169 \text{ mol/mol}$   
 $M_{H2O} = 18.01528 \text{ g/mol}$   
 $M_{MIX} = 28.96559 \cdot (1 - 0.0169) + 18.01528 \cdot 0.0169$   
 $M_{MIX} = 28.7805 \text{ g/mol}$

(v) For the full range of diluted exhaust and air, you may assume a constant molar mass of the mixture,  $M_{mix}$  such that the assumed molar mass differs from the actual molar mass by no more than  $\pm 1\%$  for all calibration and all testing. This might occur if you sufficiently control the amount of water in calibration air and in dilution air, and this might occur if you remove sufficient water from both calibration air and dilution air. Table 2 of this section gives examples of permissible emission testing dilution air dewpoints versus calibration air dewpoints.

TABLE 2. OF § 1065.640.—PERMISSIBLE RANGES OF DILUTION AIR DEWPOINT VERSUS CALIBRATION DEWPOINT WHERE A CONSTANT  $M_{mix}$  MAY BE ASSUMED

| If calibration $T_{dew}$ | Assume constant $M_{mix}$ | For emissions test $T_{dew}$ range <sup>a</sup> |
|--------------------------|---------------------------|---|
| °C                       | g/mol                     | °C  |
| dry                      | 28.96559                  | dry to 18                                       |
| 0                        | 28.89263                  | dry to 21                                       |
| 5                        | 28.86148                  | dry to 22                                       |
| 10                       | 28.81911                  | dry to 24                                       |
| 15                       | 28.76224                  | dry to 26                                       |
| 20                       | 28.68685                  | -8 to 28  |
| 25                       | 28.58806                  | 12 to 31  |
| 30                       | 28.46005                  | 23 to 34  |

<sup>a</sup> Range valid for all calibration and emissions testing over the barometric pressure range (80.000 to 103.325) kPa.

(3) *Calibration equation for SSV and CFV.* For each data point collected in § 1065.340, solve for  $C_d$ . The following example illustrates the use of the governing equations for the SSV. Note that for the case of the CFV, the equation for  $C_d$  would be the same. However, for  $C_f$  you would use your values of  $B$  and  $\gamma$  to determine  $C_f$  iteratively as described in paragraph (b)(1) of this section, or you would look up a constant value of  $C_f$  for all calibration and testing in Table 1 of § 1065.640.

$$C_d = \dot{n}_{ref} \cdot \frac{\sqrt{Z \cdot M_{mix} \cdot R \cdot T_{in}}}{C_f \cdot A_t \cdot p_{in}}$$

$$C_f = \left[ \frac{2 \cdot \gamma \cdot \left( 1 - r \frac{\gamma-1}{\gamma} \right)}{(\gamma-1) \cdot \left( r \frac{-2}{\gamma} - \beta^4 \right)} \right]^{\frac{1}{2}}$$

$$r_{SSV} = 1 - \frac{\Delta p}{P_{in}}$$

Example:

$\dot{n}_{ref} = 57.625 \text{ mol/s}$   
 $Z = 1$   
 $M_{mix} = 28.7805 \text{ g/mol}$   
 $R = 8.314472 \text{ J/mol}\cdot\text{K}$   
 $T_{in} = 298.15 \text{ K}$   
 $A_t = 0.01824 \text{ m}^2$   
 $P_{in} = 99.132 \text{ kPa}$   
 $\gamma = 1.399$   
 $\beta = 0.8$   
 $\Delta p = 2.312 \text{ kPa}$   
 $C_m = 1000 \text{ g/kg}$   
 $C_p = \text{Pa/kPa}$

$$r_{SSV} = 1 - \frac{\Delta p}{P_{in}}$$

$$r_{SSV} = 0.977$$

$$C_f = \left[ \frac{2 \cdot 1.399 \cdot \left( 1 - 0.977 \frac{1.399-1}{1.399} \right)}{(1.399-1) \cdot \left( 0.977^{1.399} - 0.8^4 \right)} \right]^{\frac{1}{2}}$$

$$C_f = 0.274$$

$$C_d = 57.625 \cdot \frac{\sqrt{1 \cdot 28.7805 \cdot 8.314472 \cdot 298.15/1000}}{0.274 \cdot 0.01824 \cdot 99.132 \cdot 1000}$$

$$C_d = 0.981$$

(i) *SSV calibration.* For each data point collected in § 1065.340, also calculate  $Re^\#$  at the throat of the venturi. Because the dynamic viscosity,  $\mu$ , is needed to compute  $Re^\#$ , you may use your own fluid viscosity model to determine  $\mu$ , using good engineering judgment. Alternatively, you may use the Sutherland three coefficient viscosity model for air at moderate

pressures and temperatures. An example of this is shown in the following example calculation for  $Re^\#$ :

$$Re^\# = \frac{4 \cdot M_{\text{mix}} \cdot \dot{n}_{\text{ref}}}{\pi \cdot d \cdot \mu}$$

Sutherland model:

$$\mu = \mu_0 \cdot \left( \frac{T_{\text{in}}}{T_0} \right)^{\frac{3}{2}} \cdot \left( \frac{T_0 + S}{T_{\text{in}} + S} \right)$$

$$\mu = 1.7894 \cdot 10^{-5} \cdot \left( \frac{298.15}{273.11} \right)^{\frac{3}{2}} \cdot \left( \frac{273.11 + 110.56}{298.15 + 110.56} \right)$$

$$\mu = 1.916 \cdot 10^{-5} \text{ kg/(m}\cdot\text{s)}$$

$$Re^\# = \frac{4 \cdot 28.7805 \cdot 57.625}{3.14159 \cdot 0.1524 \cdot 1.916 \cdot 10^{-5} \cdot 1000}$$

$$Re^\# = 7.2317 \cdot 10^5$$

(ii) Create a regression equation to calculate  $C_d$  versus  $Re^\#$ . You may use any mathematical expression such as a least-square polynomial or a power series. The regression equation must cover the flow range of  $Re^\#$  expected during testing.

(iii) The regression equation must predict  $C_d$  values within  $\pm 0.5\%$  of the individual  $C_d$  values determined from calibration.

(iv) If the  $\pm 0.5\%$  criterion is met, transfer the regression equation to the SSV real time calculation system for use in emission tests as described in § 1065.642. Do not use the equation beyond the upper and lower calibration points used to determine the equation.

(v) If the  $\pm 0.5\%$  criterion is not met for an individual data point, based upon good engineering judgment, you may omit data points and recalculate the regression equation, provided you use at least 7 points that meet the criterion. Do

not use the equation beyond the upper and lower calibration points used to determine the equation. If omitting points does not resolve outliers, take corrective action. For example, check for leaks or repeat the calibration process. If you must repeat the process, we recommend applying tighter tolerances to measurements and allow more time for flows to stabilize.

(vi) *CFV calibration.* Calculate the mean and standard deviation of all the  $C_d$  as described in § 1065.602. If the standard deviation is less than or equal to 0.3% of the mean, use the mean  $C_d$  in flow equations as described in § 1054.642, and use the CFV only down to the lowest inlet pressure measured during calibration. If the standard deviation exceeds 0.3% of the mean, omit the data point collected at the lowest venturi inlet pressure. Recalculate the mean and standard deviation and determine if the new standard deviation is less than or equal to 0.3% of the new mean. If it is, then use that mean  $C_d$  in flow calculations and use the CFV down to the lowest inlet pressure of the remaining data points. If the standard deviation still exceeds 0.3% of the mean, continue omitting the data point at the lowest inlet pressure and recalculating the

$$\mu_0 = 1.7894 \cdot 10^{-5} \text{ kg/(m}\cdot\text{s)}$$

$$T_0 = 273.11 \text{ K}$$

$$S = 110.56 \text{ K}$$

Example:

$$M_{\text{mix}} = 28.7805 \text{ g/mol}$$

$$\dot{n}_{\text{ref}} = 57.625 \text{ mol/s}$$

$$d\tau = 0.1524 \text{ m}$$

$$T_{\text{in}} = 298.15 \text{ K}$$

$$C_m = 1000 \text{ g/kg}$$

standard deviation and the mean. If the number of remaining data points becomes less than seven, take corrective action. For example, check for leaks or repeat the calibration process. If you must repeat the process, we recommend applying tighter tolerances to measurements and allow more time for flows to stabilize.

#### § 1065.642 SSV, CFV, and PDP flow rate calculations.

(a) *PDP flow rate.* Based on the slopes and intercepts calculated in § 1065.640 for the speed that you operate your PDP during an emission test, calculate flow rate,  $\dot{n}$  as follows:

$$\dot{n} = f_{\text{PDP}} \cdot \frac{P_{\text{in}} \cdot V_{\text{rev}}}{R \cdot T_{\text{in}}}$$

$$V_{\text{rev}} = \frac{a_1}{f_{\text{PDP}}} \cdot \sqrt{\frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{in}}}} + a_0$$

Example:

$$f_{\text{PDP}} = 755 \text{ rev/min}$$

$$P_{\text{in}} = 98.575 \text{ kPa}$$

$$R = 8.314472 \text{ J/(mol}\cdot\text{K)}$$

$$T_{\text{in}} = 323.5 \text{ K}$$

$$a_1 = 50.43$$

$$a_0 = 0.056$$

$$P_{\text{out}} = 99.950 \text{ kPa}$$

$$C_p = 1000 \text{ (J/m}^3\text{)/kPa}$$

$$c_t = 60 \text{ s/min}$$

$$V_{\text{rev}} = \frac{50.43}{755} \cdot \sqrt{\frac{99.950 - 98.575}{98.575}} + 0.056$$

$$\dot{n} = 755 \cdot \frac{98.575 \cdot 0.06389}{8.314472 \cdot 323.5} \cdot \frac{1000}{60}$$

(b) *SSV flow rate.* Based on the  $C_d$  versus  $Re^{\#}$  regression you determined as described in § 1065.640, calculate SSV flow rate,  $\dot{n}$  during an emission test as follows:

$$V_{\text{rev}} = 0.06389 \text{ m}^3/\text{rev}$$

$$\dot{n} = 29.464 \text{ mol/s}$$

$$\dot{n} = C_d \cdot C_f \cdot \frac{A_t \cdot P_{\text{in}}}{\sqrt{Z \cdot M_{\text{mix}} \cdot R \cdot T_{\text{in}}}}$$

$$C_d = 0.998 - 0.00653 \cdot \sqrt{\frac{10^6}{Re^{\#}}}$$

$$C_f = \frac{\left[ 2 \cdot \gamma \cdot \left( 1 - r^{\frac{\gamma-1}{\gamma}} \right) \right]^{\frac{1}{2}}}{(\gamma - 1) \cdot \left( r^{\frac{-2}{\gamma}} - \beta^4 \right)}$$

$$r_{\text{SSV}} = 1 - \frac{\Delta p}{P_{\text{in}}}$$

Example:

$$A_t = 0.01824 \text{ m}^2$$

$$P_{\text{in}} = 99.132 \text{ kPa}$$

$$Z = 1$$

$$M_{\text{mix}} = 28.7805 \text{ g/mol}$$

$$R = 8.314472 \text{ J/mol}\cdot\text{K}$$

$$T_{\text{in}} = 298.15 \text{ K}$$

$$Re^{\#} = 7.232 \cdot 10^5$$

$$\gamma = 1.399$$

$$\beta = 0.8$$

$$\Delta p = 2.31 \text{ kPa}$$

$$C_m = 1000 \text{ g/kg}$$

$$C_p = 1000 \text{ Pa/kPa}$$

$$r_{\text{SSV}} = 1 - \frac{2.312}{99.132}$$

$$C_f = 0.274$$

$$r_{\text{SSV}} = 0.977$$

$$C_d = 0.998 - 0.00653 \cdot \sqrt{\frac{10^6}{7.232 \cdot 10^5}}$$

$$C_f = \frac{\left[ 2 \cdot 1.399 \cdot \left( 1 - 0.977^{\frac{1.399-1}{1.399}} \right) \right]^{\frac{1}{2}}}{(1.399 - 1) \cdot \left( 0.977^{\frac{-2}{1.399}} - 0.8^4 \right)}$$

$$C_d = 0.990$$

$$\dot{n} = 0.990 \cdot 0.274 \cdot \frac{0.01824 \cdot 99.132 \cdot 1000}{\sqrt{1 \cdot 28.7805 \cdot 8.314472 \cdot 298.15/1000}}$$

$$\dot{n} = 58.173 \text{ mol/s}$$

(c) *CFV flow rate.* Based on the mean  $C_d$  and other constants you determined as described in § 1065.640, calculate CFV flow rate,  $\dot{n}$  during an emission test as follows:

$$\dot{n} = C_d \cdot C_{f\text{CFV}} \cdot \frac{A_t \cdot P_{\text{in}}}{\sqrt{Z \cdot M_{\text{mix}} \cdot R \cdot T_{\text{in}}}}$$

Example:

$$C_d = 0.985$$

$$C_{f\text{CFV}} = 0.7219$$

$$A_t = 0.00456 \text{ m}^2$$

$$P_{\text{in}} = 98.836 \text{ kPa}$$

$$Z = 1$$

$$M_{\text{mix}} = 28.7805 \text{ g/mol}$$

$$R = 8.314472 \text{ J/mol}\cdot\text{K}$$

$$T_{\text{in}} = 378.15 \text{ K}$$

$$\gamma = 1.399$$

$$\beta = 0.7$$

$$C_m = 1000 \text{ g/kg}$$

$$C_p = 1000 \text{ Pa/kPa}$$

$$\dot{n} = 0.985 \cdot 0.7219 \cdot \frac{0.00456 \cdot 98.836 \cdot 1000}{\sqrt{1 \cdot 28.7805 \cdot 8.314472 \cdot 378.15/1000}}$$

$$\dot{n} = 33.690 \text{ mol/s}$$

#### § 1065.645 Amount of water in an ideal gas.

(a) For various emission calculations, you must calculate the amount of water in an ideal gas,  $X_{H_2O}$ .

(1) Based on the measured dewpoint,  $T_{\text{dew}}$  or frost point  $T_{\text{ice}}$  and the triple point of water,  $T_0$ , use the formulations of the World Meteorological Organization (General Meteorological Standards and Recommended Practices,

Appendix A, WMO Technical Regulations, WMO-No. 49, 2000, incorporated by reference at § 1065.1010), to first calculate the pressure of water,  $p_{H_2O}$  in an ideal gas as follows:

$$P_{\text{sat}} = \frac{10^{\left[ 10.79574 \cdot \left( 1 - \frac{T_0}{T_{\text{dew}}} \right) - 5.02800 \cdot \log \left( \frac{T_{\text{dew}}}{T_0} \right) + 1.50475 \cdot 10^{-4} \cdot \left( 1 - 10^{-8.2969 \cdot \left( \frac{T_{\text{dew}}}{T_0} - 1 \right)} \right) \right] + 0.42873 \cdot 10^{-3} \cdot \left( 10^{-4.76955 \cdot \left( 1 - \frac{T_0}{T_{\text{dew}}} \right)} - 1 \right) + 0.78614}{10}$$

$$T_0 = 273.16 \text{ K}$$

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

Example:

$$T_{\text{dew}} = 9.5 + 273.15 = 282.65 \text{ K}$$

$$P_{\text{sat}} = \frac{10^{\left[ 10.79574 \cdot \left( 1 - \frac{273.16}{282.65} \right) - 5.02800 \cdot \log \left( \frac{282.65}{273.16} \right) + 1.50475 \cdot 10^{-4} \cdot \left( 1 - 10^{-8.2969 \cdot \left( \frac{282.65}{273.16} - 1 \right)} \right) \right] + 0.42873 \cdot 10^{-3} \cdot \left( 10^{-4.76955 \cdot \left( 1 - \frac{273.16}{282.65} \right)} - 1 \right) + 0.78614}{10}$$

$$P_{\text{sat}} = 1.186 \text{ kPa}$$

(2) And for frost point:

$$P_{\text{H}_2\text{O}} = \frac{10^{\left[ -9.09685 \cdot \left( \frac{T_0}{T_{\text{ice}}} - 1 \right) - 3.56654 \cdot \log \left( \frac{T_0}{T_{\text{ice}}} \right) + 0.87682 \cdot \left( 1 - \frac{T_{\text{ice}}}{T_0} \right) + 0.78614 \right]}}{10}$$

Example:

$$T_0 = 273.16 \text{ K}$$

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

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

$$P_{\text{H}_2\text{O}} = \frac{10^{\left[ -9.09685 \cdot \left( \frac{273.16_0}{257.75} - 1 \right) - 3.56654 \cdot \log \left( \frac{273.16_0}{257.75} \right) + 0.87682 \cdot \left( 1 - \frac{257.75}{273.16_0} \right) + 0.78614 \right]}}{10}$$

$$P_{\text{H}_2\text{O}} = 0.1591 \text{ kPa}$$

(3) The equation that uses dewpoint has been experimentally confirmed from (0 to 100) °C, and the same formula may be used over super-cooled water from (-50 to 0) °C with insignificant error. The equation for frostpoint is valid from (-100 to 0) °C.

(b) You may also use other formulas to convert dewpoint or frostpoint to  $p_{\text{H}_2\text{O}}$ , provided that their use does not affect your ability to show compliance with the applicable standards. Formulas such as the commonly known the Goff-Gratch formula may be used. Note however that the Wexler-Greenspan formula that we previously specified is not valid for dewpoints below 0 °C.

(c) To calculate the amount of water in an ideal gas, divide  $p_{\text{H}_2\text{O}}$  by the absolute pressure (for example, barometric pressure) at which you

measured dewpoint or frostpoint, as follows:

$$x_{\text{H}_2\text{O}} = \frac{P_{\text{sat}}}{P_{\text{total}}}$$

Example:

$$P_{\text{sat}} = 1.186 \text{ kPa}$$

$$P_{\text{total}} = 99.980 \text{ kPa}$$

$$x_{\text{H}_2\text{O}} = \frac{1.186}{99.980}$$

$$x_{\text{H}_2\text{O}} = 0.01186 \text{ mol/mol}$$

#### § 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 ways to calculate brake-specific emissions, as follows:

(1) Calculate the total mass of emissions and then divide it by the total work generated over the test interval. In this section, we describe how to calculate the total mass of different emissions. We describe how to calculate total work. Divide the total mass by the total work to determine brake-specific emissions, as follows:

$$e = \frac{m}{W}$$

Example:

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

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

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

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

(2) For steady-state testing, you may calculate the ratio of emission mass rate to power. In this special case you determine a mean mass rate of emissions during steady-state operation, and then divide that rate by the steady-state mean power. The result is a brake-specific emission value calculated as follows:

$$e = \frac{\bar{m}}{\bar{P}}$$

*Example:*

$$\bar{m}_{\text{NMHC}} = 2.885 \text{ mg/s}$$

$$\bar{P} = 54.342 \text{ kW}$$

$$C_r = 3600 \text{ s/hr}$$

$$C_m = 1000 \text{ mg/g}$$

$$e_{\text{NMHC}} = \frac{2.885 \cdot 3600}{54.342 \cdot 1000}$$

$$e_{\text{NMHC}} = 0.191 \text{ g/(kW}\cdot\text{hr)}$$

(3) Calculate the ratio of total mass to total work. This is a special case in which you use a signal linearly proportional to raw exhaust 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. In this case we do not require any flow meter to be accurate, but we do require any flow meter you use must meet the applicable linearity and repeatability specifications in subpart D (performance checks) or subpart J (field testing) of this part. The result is a brake-specific emission value calculated as follows:

$$e = \frac{\bar{m}}{\bar{W}}$$

*Example:*

$$\bar{m}_{\text{CO}} = 805.5 \text{ ~g}$$

$$\bar{w} = 52.102 \text{ ~kW}\cdot\text{hr}$$

$$e_{\text{CO}} = \frac{805.5}{52.102}$$

$$e_{\text{CO}} = 2.520 \text{ g/(kW}\cdot\text{hr)}$$

(b) *Total mass of emissions.* To determine brake-specific emissions for a test interval under paragraph (a)(1) of this section, calculate the total mass of each emission. To calculate the total mass of an emission, you multiply a

concentration by its respective flow. Follow these steps to calculate total mass of emissions:

(1) *Concentration corrections and calculations.* Before multiplying concentrations by a flow, perform the following calculations on recorded concentrations, in order, as follows:

(i) Correct all concentrations for drift, including dilution air background concentrations. Correct for drift as described in § 1065.657.

(ii) Optionally, correct all concentrations for instrument noise, including dilution air background concentrations. Correct for noise as described in § 1065.658.

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

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

(v) If you performed an emission test with an oxygenated fuel (see subpart E or this part) calculate any NMHCE concentrations including dilution air background concentrations as described in § 1065.665.

(2) *Continuous sampling.* For continuous sampling you frequently record a continuously updated concentration signal. You may measure this concentration from a changing flow rate or a constant flow rate, as follows:

(i) 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 flows changing flows that require a continuous multiplication of concentration times 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,  $m$ . The following is a continuous sampling with variable flow example:

$$m = M \cdot \sum_{i=1}^N x_i \cdot \dot{n}_i \cdot \Delta t$$

$$\Delta t = \frac{1}{f_{\text{record}}}$$

*Example:*

$$M_{\text{NMHC}} = 13.875389 \text{ g/mol}$$

$$N = 1200$$

$$x_{\text{NMHC}1} = 84.5 \text{ }\mu\text{mol/mol}$$

$$x_{\text{NMHC}2} = 86.0 \text{ }\mu\text{mol/mol}$$

$$\dot{n}_{\text{exh}1} = 2.876 \text{ mol/s}$$

$$\dot{n}_{\text{exh}2} = 2.224 \text{ mol/s}$$

$$f_{\text{record}} = 1 \text{ Hz}$$

$$C_{\text{mol}} = 1000000 \text{ }\mu\text{mol/mol}$$

$$\Delta t = \frac{1}{1} = 1 \text{ s}$$

$$m_{\text{NMHC}} = 13.875389 \cdot (84.5 \cdot 2.876 + 86.0 \cdot 2.224 + \dots + x_{\text{NMHC}1200} \cdot \dot{n}_{\text{exh}1200}) \cdot 1 \cdot 1000000$$

$$m_{\text{NMHC}} = 25.23 \text{ g}$$

(ii) If you continuously sample from a constant exhaust flow rate, you may calculate the mean concentration recorded over the test interval and treat the mean as a batch sample (e.g., bag sample) as described in paragraph (b)(3)(ii) of this section. We consider the following flows 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.* The concentration may also be a single concentration from a proportionally extracted batch sample (e.g., a bag). In this case, you 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) If you batch sample from a changing exhaust flow rate, extract a sample proportional to the changing exhaust flow rate. We consider the following flows 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. 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,  $\bar{M}_{\text{PM}}$ , simply multiply the total flow by  $\bar{M}_{\text{PM}}$ . The result is the total mass of PM,  $m_{\text{PM}}$ .

The following is a batch sample extracted from a variable flow rate example:

$$m = M \cdot \bar{x} \cdot \sum_{i=1}^N \dot{n}_i \cdot \Delta t$$

$$\Delta t = \frac{1}{f_{\text{record}}}$$

Example:

$$M_{\text{NO}_x} = 46.0055 \text{ g/mol}$$

$$N = 9000$$

$$x_{\text{NO}_x} = 85.6 \text{ } \mu\text{mol/mol}$$

$$\dot{n}_{\text{dexh1}} = 25.534 \text{ mol/s}$$

$$\dot{n}_{\text{dexh2}} = 26.950 \text{ mol/s}$$

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

$$C_{\text{mol}} = 1000000 \text{ } \mu\text{mol/mol}$$

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

$$m_{\text{NO}_x} = 46.0055 \cdot 85.6(25.534 + 26.950$$

$$+ \dots + \dot{n}_{\text{dexh9000}}) \cdot 0.2 \cdot 1000000$$

$$m_{\text{NO}_x} = 4.201 \text{ g}$$

(ii) If you batch sample from a constant exhaust flow rate, extract a sample at a constant flow rate. We consider the following flows 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 flow rate from which you extracted the constant flow rate sample. Multiply the mean concentration of the batch sample by the mean 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,  $\bar{M}_{\text{PM}}$ , simply multiply the total flow by  $\bar{M}_{\text{PM}}$ . The result is the total mass of  $\text{PM}_{\text{mPM}}$ .

(iii) The following is a batch sample extracted from a constant flow rate example:

(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 steady-state mass rate of the emission. Then calculate the steady-state power. Divide the mean mass rate of the emission by the mean power to determine steady-state brake-specific emissions.

(1) To calculate the mass rate of an emission, multiply its mean

$$m = M \cdot \bar{x} \cdot \bar{n} \cdot \Delta t$$

$$M \cdot \bar{x} = \bar{M}_{\text{PM}}$$

Example:

$$\bar{M}_{\text{PM}} = 0.144 \text{ mg/mol}$$

$$\dot{n}_{\text{dexh}} = 57.692 \text{ mol/s}$$

$$\Delta t = 20 \text{ min}$$

$$C_t = 60 \text{ s/min}$$

$$C_m = 1000 \text{ mg/g}$$

$$m_{\text{PM}} = \frac{0.144 \cdot 57.692 \cdot 20 \cdot 60}{1000}$$

$$m_{\text{PM}} = 37.661 \text{ g}$$

(4) *Diluted exhaust sampling; continuous or batch.* If you sampled emissions from diluted exhaust, you must consider two additional steps.

(i) If you diluted a sample at a constant ratio of dilution air flow rate to exhaust flow rate (raw or dilute), you must multiply your total mass emissions by the sum of the dilution ratio, DR, plus one. The following is an example of a secondary dilution system for sampling PM from a CVS:

$$m_{\text{PM}} = m_{\text{PMdil}} \cdot (\text{DR} + 1)$$

Example:

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

$$\text{DR} = 5:1$$

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

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

(ii) You may optionally measure background emissions in dilution air by either continuous sampling or batch sampling. You may then subtract the background you would have otherwise attributed to your engine as described in § 1065.667.

(5) *NO<sub>x</sub> correction for intake-air humidity.* Correct the total mass of NO<sub>x</sub> based on intake-air humidity as described in § 1065.670. Note that if you performed diluted exhaust sampling, perform this correction after correcting for any dilution air background.

(c) *Total work.* To determine brake-specific emissions for a test interval as

$$W = 16.75 \text{ kW} \cdot \text{hr}$$

concentration (e.g.,  $\bar{x}$ ) by its respective mean 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,

$$\bar{m}$$

In the case of PM emissions, where the mean PM concentration is already in

described in paragraph (a)(1) of this section, you must also calculate the total work. To calculate total work, multiply the feedback engine speed by its respective feedback torque and apply the appropriate units conversion factors. This results in the power of the engine. Integrate the power over a test interval to determine the total work. If your standard is in the units g/hp.hr use the following conversion factor: 1 hp = 550 ft lbf/s = 0.77456999 kW, and round the resulting value. The following is an example:

$$W = \sum_{i=1}^N P_i \cdot \Delta t$$

$$P_i = f_{ni} \cdot T_i$$

$$\Delta t = \frac{1}{f_{\text{record}}}$$

Example:

$$N = 9000$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

units of mass per mole of sample,  $M_{\text{PM}}$ , simply multiply the mean flow rate,

$$\bar{n}$$

by  $\bar{M}_{\text{PM}}$ . The result is the mass rate of PM,

$\bar{m}_{\text{PM}}$ .

(2) To calculate power, multiply mean engine speed,  $\bar{f}_n$ , by its respective mean torque,  $\bar{T}$ , and apply the appropriate units conversion factors. The result is the mean power of the engine,  $\bar{P}$ .

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

(4) The following is an example of how to calculate mean mass rate and mean power:

$$\bar{m} = M \cdot \bar{x} \cdot \bar{n}$$

$$\bar{P} = \bar{f}_n \cdot \bar{T}$$

Examples:

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

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

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

$$C_{mol} = 1000 \text{ mmol/mol}$$

$$\bar{f} = 3584.5 \text{ rev/min}$$

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

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

$$C_t = 60 \text{ s/min}$$

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

$$\bar{m} = \frac{28.0101 \cdot 12.00 \cdot 1.530}{1000}$$

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

$$\bar{P} = \frac{3584.5 \cdot 121.50 \cdot 2 \cdot \pi}{1000 \cdot 60}$$

$$\bar{P} = 45.61 \text{ kW}$$

(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. The result is a brake-specific emission.

(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 flow rate,  $\dot{n}$ , or the total flow,  $n$  with a signal that is linearly proportional to flow rate, or linearly proportional to total flow,  $\bar{n}$ .

(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,  $e_{fuel}$  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 flow rate,  $\dot{n}$ , in paragraph (e)(1) of this section. The following is an example of how to determine a signal proportional to total work over a test interval:

$$\tilde{W} = \sum_{i=1}^N \tilde{P}_i \cdot \Delta t$$

$$\tilde{P}_i = \frac{\tilde{m}_{fueli}}{e_{fuel}}$$

$$\tilde{m}_{fueli} = \frac{1}{w_{fuel}} \cdot \frac{M_C \cdot \tilde{n}_i \cdot x_{Cproddryi}}{1 + x_{H_2O_i}}$$

$$\Delta t = \frac{1}{f_{record}}$$

Example:

$$N = 3000$$

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

$$e_{fuel} = 285 \text{ g/(kW}\cdot\text{hr)}$$

$$w_{fuel} = 0.869 \text{ g/g}$$

$$M_C = 12.0107 \text{ g/mol}$$

$$\bar{n}_1 = 3.922 \sim \text{mol/s}$$

$$x_{Cproddry1} = 91.634 \text{ mmol/mol}$$

$$x_{H_2O1} = 26.16 \text{ mmol/mol}$$

$$\bar{n}_2 = 4.139 \sim \text{mol/s}$$

$$x_{Cproddry2} = 98.005 \text{ mmol/mol}$$

$$x_{H_2O2} = 27.21 \text{ mmol/mol}$$

$$C_{mol} = 1000 \text{ mmol/mol}$$

$$C_t \text{ s/hr}$$

$$\tilde{W} = \frac{12.0107 \cdot \left[ \frac{3.922 \cdot \frac{91.634}{1000}}{1 + \frac{26.16}{1000}} + \frac{4.139 \cdot \frac{98.005}{1000}}{1 + \frac{27.21}{1000}} + \tilde{n}_{3000} \cdot \frac{x_{Cpdry3000}}{1 + \frac{x_{H_2O3000}}{1000}} \right] \cdot 0.2}{1}$$

$$\tilde{W} = 5.09 \sim \text{kW}\cdot\text{hr}$$

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

(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 (i.e., g/hp·hr.).

(1) *General.* To replace a number having a given number of digits with a number having a smaller number of digits, follow these rules:

(i) If the digits to be discarded begin with a digit less than 5, the digit preceding the 5 is not changed. Example : 6.9749515 rounded to 3 digits is 6.97.

(ii) If the digits to be discarded begin with a 5 and at least one of the

following digits is greater than 0, the digit preceding the 5 is increased by 1. Examples : 6.9749515 rounded to 2 digits is 7.0, 6.9749515 rounded to 5 digits is 6.9750.

(iii) If the digits to be discarded begin with a 5 and all of the following digits are 0, the digit preceding the 5 is unchanged if it is even and increased by 1 if it is odd. (Note that this means that the final digit is always even.) Examples : 6.9749515 rounded to 7 digits is 6.974952, 6.974950 5 rounded to 7 digits is 6.974950.

(2) *Rounding converted numerical values.* In most cases the product of the unconverted numerical value and a conversion factor will be a numerical value with a number of digits that exceeds the number of significant digits of the unconverted numerical value.

Proper conversion procedure requires rounding this converted numerical value to the number of significant digits that is consistent with the maximum possible rounding error of the unconverted numerical value. Example : To express the value 1 = 36 ft in meters, use the factor 0.3048 and write 1 = 36 ft 3 0.3048 m/ft = 10.9728 m = 11.0 m. The final result, 1 = 11.0 m, is based on the following reasoning: The numerical value "36" has two significant digits, and thus a relative maximum possible rounding error (abbreviated RE) of 0.5/36 = 1.4% because it could have resulted from rounding the number 35.5, 36.5, or any number between 35.5 and 36.5. To be consistent with this RE, the converted numerical value "10.9728" is rounded to 11.0 or three significant digits

because the number 11.0 has an RE of  $0.05/11.0 = 0.45\%$ . Although this 0.45% RE is one-third of the 1.4% RE of the unconverted numerical value "36," if the converted numerical value "10.9728" had been rounded to 11 or two significant digits, information contained in the unconverted numerical value "36" would have been lost. This is because the RE of the numerical value "11" is  $0.5/11 = 4.5\%$ , which is three times the 1.4% RE of the unconverted numerical value "36." This example therefore shows that when selecting the number of digits to retain in the numerical value of a converted quantity, one must often choose between discarding information or providing unwarranted information. Consideration of the end use of the converted value can often help one decide which choice to make. Note: Consider that one had been told initially that the value  $1 = 36$  ft had been rounded to the nearest inch. Then in this case, since 1 is known to within 1 in, the RE of the numerical value "36" is  $1 \text{ in}/(36 \text{ ft } 3 \text{ 12 in/ft}) = 0.23\%$ . Although this is less than the 0.45% RE of the number 11.0, it is comparable to it. Therefore, the result  $1 = 11.0$  m is still given as the converted value. Note that the numerical value "10.97" would give excessive unwarranted information because it has an RE that is one-fifth of 0.23%.

**§ 1065.655 Chemical balances of fuel, intake air, and exhaust.**

(a) *General.* Chemical balances of fuel, intake air, and exhaust may be used to calculate ratios of their flows, the amount of water in their flows, and the concentration of constituents in their flows. Along with the flow rate of either fuel, intake air, or exhaust you may use chemical balances to determine the flows of the other two. For example, you may use chemical balances along with exhaust flow to determine fuel flow and intake flow.

(b) *Procedures that require chemical balances.* We require chemical balances when you determine the following:

(1) A value proportional to total work,  $\dot{W}$ , when you choose to determine brake-specific emissions as described in § 1065.650(e).

(2) The amount of water in a raw or diluted exhaust flow,  $x_{H_2O}$ , when you

do not measure the amount of water in a flow to correct for the amount water removed, as described in § 1065.659(c)(2).

(3) The flow-weighted average fraction of dilution air in diluted exhaust,  $DF$ , when you do not measure dilution air flow to correct for background emissions as described in § 1065.667(c).

(c) *Chemical balance procedure.* The calculations for a chemical balance involve a system of equations that require iteration. We recommend using a computer to solve this system of equations. You must guess the initial values of up to three quantities: the amount of water in the measured flow,  $x_{H_2O}$ , fraction of dilution air in diluted exhaust,  $DF$ , and the amount of products on a  $C_1$  basis per dry mole of dry measured flow,  $x_{C_{proddry}}$ . For each emissions concentration,  $x$ , and amount of water  $x_{H_2O}$ , you must determine their completely dry concentrations,  $x_{dry}$  and  $x_{H_2Odry}$ . You must also use your fuel's atomic hydrogen to carbon ratio,  $\alpha$ , and oxygen to carbon ratio,  $\beta$ . For your fuel, you may measure  $\alpha$  and  $\beta$  or you may use the default values in Table 1 of § 1065.650. Use the following steps to complete a chemical balance:

(1) Convert your measured concentrations such as,  $x_{CO_2meas}$ ,  $x_{NOmeas}$ , and  $x_{H_2Oint}$ , to dry concentrations by dividing them by one minus the amount of water present during their respective measurements:  $x_{H_2OxCO_2}$ ,  $x_{H_2OxNO}$ , and  $x_{H_2Oint}$ . If the amount of water present during a "wet" measurement is the same as the unknown amount of water in the exhaust flow,  $x_{H_2O}$ , iteratively solve for that value in the system of equations. If you measure only total  $NO_x$  and not  $NO$  and  $NO_2$  separately, use good engineering judgement to split your total  $NO_x$  between  $NO$  and  $NO_2$  for the chemical balances. For example, if you measure emissions from a stoichiometric spark-ignition engine, you may assume all  $NO_x$  is  $NO$ . For a compression-ignition engine, you may assume  $NO_x$  is 75%  $NO$  and 25%  $NO_2$ . For  $NO_2$  storage aftertreatment systems, you may assume  $NO_x$  is 75%  $NO_2$  and 25%  $NO$ . Note that for emissions calculations you must use the molar mass of  $NO_2$  for the molar mass of all

$NO_x$ , regardless of the actual  $NO_2$  fraction of  $NO_x$ .

(2) Enter the equations in paragraph (c)(3) of this section into a computer program to iteratively solve for  $x_{H_2O}$  and  $x_{C_{proddry}}$ . If you measure raw exhaust flow, set  $DF$  equal to zero (0). If you measure diluted exhaust flow, iteratively solve for  $DF$ . Use good engineering judgment to guess initial values for  $x_{H_2O}$ ,  $x_{C_{proddry}}$ , and  $DF$ . We recommend guessing an initial amount of water that is about twice the amount of water in your intake or dilution air. We recommend guessing an initial value of  $x_{C_{proddry}}$  as the sum of your measured  $CO_2$ ,  $CO$ , and  $THC$  values. If you measure diluted exhaust, we also recommend guessing an initial  $DF$  between 0.75 and 0.95, such as 0.8. Perform iteration until the most recently updated guesses are all within  $\pm 1\%$  of their respective most recently calculated values.

(3) In the equations that follow, we use the following symbols and subscripts:

$x^{H_2O}$  = amount of water in measured flow  
 $x^{H_2Odry}$  = amount of water per dry mole of measured flow  
 $x^{C_{proddry}}$  = amount of carbon products on a  $C_1$  basis per dry mole of measured flow  
 $DF$  = fraction of dilution air in measured flow—assuming stoichiometric exhaust  
 $x^{prod/intdry}$  = amount of dry stoichiometric products per dry mole of intake air  
 $x^{O_2proddry}$  = amount of oxygen products on an  $O_2$  basis per dry mole of measured flow  
 $x^{[emission]dry}$  = amount of emission per dry mole of measured flow  
 $x^{[emission]meas}$  = amount of emission in measured flow  
 $x^{H_2O[emission]meas}$  = amount of water at emission measurement location  
 $x^{H_2Oint}$  = amount of water in intake air  
 $x^{H_2Odil}$  = amount of water in dilution air  
 $x^{O_2airdry}$  = amount of oxygen per dry mole of air; 0.209445 mol/mol  
 $x^{O_2airdry}$  = amount of carbon dioxide per dry mole air; 375  $\mu\text{mol/mol}$   
 $\alpha$  = atomic hydrogen to carbon ratio in fuel  
 $\beta$  = oxygen to carbon ratio in fuel

$$x_{\text{H}_2\text{O}} = \frac{x_{\text{H}_2\text{Odry}}}{1 + x_{\text{H}_2\text{Odry}}}$$

$$x_{\text{H}_2\text{Odry}} = \frac{\alpha}{2} \cdot x_{\text{Cproddry}} + (1 - \text{DF}) \cdot \frac{x_{\text{H}_2\text{Ointdry}}}{x_{\text{prod/intdry}}} + \text{DF} \cdot x_{\text{H}_2\text{Odildry}}$$

$$x_{\text{Cproddry}} = x_{\text{CO}_2\text{dry}} + x_{\text{COdry}} + x_{\text{THCdry}}$$

$$\text{DF} = 1 - \frac{x_{\text{O}_2\text{proddry}} \cdot x_{\text{prod/intdry}}}{x_{\text{O}_2\text{airdry}}} \cdot (1 + x_{\text{H}_2\text{Ointdry}})$$

$$x_{\text{prod/intdry}} = \frac{1}{1 - \frac{1}{1 - \text{DF}} \cdot \frac{1}{2} \cdot \left( x_{\text{COdry}} - \frac{\alpha}{2} \cdot x_{\text{Cproddry}} - x_{\text{NO}_2\text{dry}} \right)}$$

$$x_{\text{O}_2\text{proddry}} = x_{\text{CO}_2\text{dry}} + \frac{1}{2} \cdot \left( x_{\text{COdry}} + \frac{\alpha}{2} \cdot x_{\text{Cproddry}} + x_{\text{NO}_2\text{dry}} \right) + x_{\text{NO}_2\text{dry}} - \beta \cdot x_{\text{Cproddry}}$$

$$x_{\text{CO}_2\text{dry}} = \frac{x_{\text{CO}_2\text{meas}}}{1 - x_{\text{H}_2\text{OCO}_2\text{meas}}} - \frac{x_{\text{CO}_2\text{airdry}}}{1 - \frac{1}{2} \cdot \left( x_{\text{COdry}} - \frac{\alpha}{2} \cdot x_{\text{Cproddry}} - x_{\text{NO}_2\text{dry}} \right)}$$

$$x_{\text{COdry}} = \frac{x_{\text{COmeas}}}{1 - x_{\text{H}_2\text{OCOmeas}}}$$

$$x_{\text{THCdry}} = \frac{x_{\text{THCmeas}}}{1 - x_{\text{H}_2\text{OTHCmeas}}}$$

$$x_{\text{H}_2\text{Ointdry}} = \frac{x_{\text{H}_2\text{Oint}}}{1 - x_{\text{H}_2\text{Oint}}}$$

$$x_{\text{H}_2\text{Odildry}} = \frac{x_{\text{H}_2\text{Odil}}}{1 - x_{\text{H}_2\text{Odil}}}$$

$$x_{\text{NO}_2\text{dry}} = \frac{x_{\text{NO}_2\text{meas}}}{1 - x_{\text{H}_2\text{ONO}_2\text{meas}}}$$

$$x_{\text{NOdry}} = \frac{x_{\text{NOmeas}}}{1 - x_{\text{H}_2\text{ONomeas}}}$$

(4) The following is an example;  
iteratively solved using the equations in  
paragraph (c)(3) of this section:

$$x_{\text{H}_2\text{O}} = \frac{35.24}{1 + \frac{35.24}{1000}} = 34.04 \text{ mmol/mol}$$

$$x_{\text{H}_2\text{Odry}} = \frac{1.8}{2} \cdot 24.69 + (1 - 0.843) \cdot \frac{17.22}{0.9338} + 0.843 \cdot 12.01 = 35.24 \text{ mmol/mol}$$

$$x_{\text{Cproddry}} = 24.614 + \frac{29.3}{1000} + \frac{47.6}{1000} = 24.69 \text{ mmol/mol}$$

$$\text{DF} = 1 - \frac{\frac{34.54}{1000} \cdot 0.9338}{0.209445} \cdot \left( 1 + \frac{17.22}{1000} \right) = 0.843$$

$$x_{\text{prod/intdry}} = \frac{1}{1 - \frac{1}{1 - 0.843} \cdot \frac{1}{2} \cdot \left( \frac{29.3}{1000000} - \frac{1.8}{2} \cdot \frac{24.69}{1000} - \frac{12.1}{1000000} \right)} = 0.9338 \text{ mol/mol}$$

$$x_{\text{O}_2\text{proddry}} = 24.614 + \frac{1}{2} \cdot \left( \frac{29.3}{1000} + \frac{1.8}{2} \cdot 24.69 + \frac{50.4}{1000} \right) + \frac{12.1}{1000} - 0.05 \cdot 24.69 = 34.54 \text{ mol/mol}$$

$$x_{\text{CO}_2\text{dry}} = \frac{24.770}{1 - \frac{8.601}{1000}} - \frac{\frac{375}{1000}}{1 - \frac{1}{2} \cdot \left( \frac{29.3}{1000000} - \frac{1.8}{2} \cdot \frac{24.69}{1000} - \frac{12.1}{1000000} \right)} = 24.614 \text{ mmol/mol}$$

$$x_{\text{COdry}} = \frac{29.0}{1 - \frac{8.601}{1000}} = 29.3 \mu\text{mol/mol}$$

$$x_{\text{THCdry}} = \frac{46}{1 - \frac{34.04}{1000}} = 47.6 \mu\text{mol/mol}$$

$$x_{\text{H}_2\text{O}_{\text{indry}}} = \frac{16.93}{1 - \frac{16.93}{1000}} = 17.22 \text{ mmol/mol}$$

$$x_{\text{H}_2\text{O}_{\text{dildry}}} = \frac{11.87}{1 - \frac{11.87}{1000}} = 12.01 \text{ mmol/mol}$$

$$x_{\text{NO}_2\text{dry}} = \frac{12.0}{1 - \frac{8.601}{1000}} = 12.1 \mu\text{mol/mol}$$

$$x_{\text{NOdry}} = \frac{50.0}{1 - \frac{8.601}{1000}} = 50.4 \mu\text{mol/mol}$$

$$x_{\text{O}_2\text{airdry}} = 0.209445 \text{ mol/mol}$$

$$x_{\text{CO}_2\text{airday}} = 375 \mu\text{mol/mol}$$

$$\alpha = 1.8$$

$$\beta = 0.05$$

TABLE 1 OF § 1065.655.—DEFAULT VALUES OF ATOMIC HYDROGEN TO CARBON RATIO,  $\alpha$ , ATOMIC OXYGEN TO CARBON RATIO,  $\beta$ , AND CARBON MASS FRACTION OF FUEL,  $w_c$ , FOR VARIOUS FUELS

| Fuel                           | Atomic hydrogen and oxygen to carbon ratios $\text{CH}\alpha\text{O}\beta$ | Carbon mass concentration, $w_c$ g/g |
|--------------------------------|--|--------------------------------------|
| Gasoline ...                   | $\text{CH}_{1.85}\text{O}_0$   | 0.866                                |
| #2 Diesel ...                  | $\text{CH}_{1.80}\text{O}_0$   | 0.869                                |
| #1 Diesel ...                  | $\text{CH}_{1.93}\text{O}_0$   | 0.861                                |
| LPG ( $\text{C}_3\text{H}_8$ ) | $\text{CH}_{2.67}\text{O}_0$   | 0.817                                |
| LNG/CNG ..                     | $\text{CH}_{3.79}\text{O}_{0.02}$  | 0.707                                |
| Ethanol .....                  | $\text{CH}_3\text{O}_{0.5}$  | 0.521                                |
| Methanol ...                   | $\text{CH}_4\text{O}_1$  | 0.375                                |

### § 1065.657 Drift validation and correction.

(a) Determine if measurement instrument drift invalidates a test. Use the following quantities and calculation to determine if drift invalidates a test:

(1) Span reference,  $x_{\text{ref}}$ .

(2) Post-test span check,  $x_{\text{spanchk}}$ .

(3) Post-test zero check,  $x_{\text{zerochk}}$ .

(4) Flow-weighted amount expected at either the standard or during a test interval, whichever is greater,  $x_{\text{exp}}$ .

(5) Calculate drift correction, as follows:

$$\text{drift correction} = \frac{\frac{x_{\text{zerochk}} - x_{\text{spanchk}}}{x_{\text{ref}}} + 1 - \frac{x_{\text{zerochk}}}{x_{\text{exp}}}}{2}$$

#### Example:

$$x_{\text{spanchk}} = 1695.8 \mu\text{mol/mol}$$

$$x_{\text{zerochk}} = -5.2 \mu\text{mol/mol}$$

$$x_{\text{ref}} = 1800.0 \mu\text{mol/mol}$$

$$x_{\text{exp}} = 435.5 \mu\text{mol/mol}$$

$$\text{drift correction} = \frac{\frac{-5.2 - 1695.8}{1800.0} + 1 - \frac{-5.2}{435.5}}{2} = 0.033 = 3.3\%$$

(b) You may correct every recorded amount for drift if drift did not invalidate the test. Use the following

quantities and calculation to correct for drift:

(1) The quantities from paragraph (a) of this section.

(2) Each recorded amount,  $\bar{x}_i$  or for batch sampling,  $\mathbf{X}$ .

(3) Correct for drift as follows:

$$x_{i \text{ drift corrected}} = \frac{\left( \frac{x_{\text{zerochk}} - x_{\text{spanchk}}}{x_{\text{ref}}} + 3 \right) \cdot x_i - x_{\text{zerochk}}}{2}$$

#### Example:

$$x_{\text{spanchk}} = 1695.8 \mu\text{mol/mol}$$

$$x_{\text{zerochk}} = -5.2 \mu\text{mol/mol}$$

$$x_{\text{ref}} = 1800.0 \mu\text{mol/mol}$$

$$x_i \text{ or } \bar{x} = 435.5 \mu\text{mol/mol}$$

$$x_{i \text{ drift corrected}} = \frac{\left( \frac{-5.2 - 1695.8}{1800.0} + 3 \right) \cdot 435.5 - (-5.2)}{2} = 450.1 \mu\text{mol/mol}$$

**§ 1065.658 Noise correction.**

(a) You may set to zero any recorded data point if that point's numerical value is smaller than the least of the following values:

(1) The measurement instrument noise determined according to § 1065.305.

(2) For lab instruments the recommended noise limit specified in Table 1 of § 1065.205.

(3) For field-testing instruments, the recommended noise limit specified in Table 1 of § 1065.915.

(b) If you perform this noise correction on samples that are corrected for background concentrations in dilution air, then noise correct the respective dilution air measurements the same way.

(c) If you perform this noise correction on a THC concentration that you use to determine NMHC, then correct the CH<sub>4</sub> concentration the same way.

**§ 1065.659 Removed water correction.**

(a) If you remove water upstream of a concentration measurement,  $x$ , or upstream of a flow measurement,  $n$ , correct for the removed water. Perform this correction based on the amount of water at the concentration measurement,  $x_{H_2O[emission]meas}$ , and at the flow meter,  $x_{H_2O}$ , whose flow is used to determine the concentration's total mass over a test interval.

(b) Downstream of where you removed water, you may determine the amount of water remaining by any of the following:

(1) Measure the dewpoint temperature and absolute pressure downstream of

the water removal location and then calculate the amount of water remaining as described in § 1065.645.

(2) If you can justify assuming saturated water vapor conditions at a given location, you may use the measured temperature at that location as the dewpoint temperature.

(3) You may also use a nominal value of absolute pressure based on an alarm setpoint, a pressure regulator setpoint, or good engineering judgment.

(c) For a corresponding concentration or flow measurement where you did not remove water, you may determine the amount of initial water by any of the following:

(1) Use any of the techniques described in paragraph (b) of this section.

(2) If the measurement is a raw exhaust measurement, you may determine the amount of water based on intake-air humidity, plus a chemical balance of fuel, intake air and exhaust as described in § 1065.655.

(3) If the measurement is a diluted exhaust measurement, you may determine the amount of water based on intake-air humidity, dilution air humidity, and a chemical balance of fuel, intake air and exhaust as described in § 1065.655.

(d) Perform a removed water correction to the concentration measurement using the following calculation:

$$x = x_{[emission]meas} \cdot \left[ \frac{1 - x_{H_2O}}{1 - x_{H_2O[emission]meas}} \right]$$

Example:

$$x_{NMHC} = \frac{PF_{CH_4} \cdot x_{THC} - x_{CH_4}}{PF_{CH_4} - PF_{C_2H_6}} - x_{NMHCinit}$$

$$RF_{CH_4} = 0.970$$

$$x_{NMHCinit} = 1.1 \mu\text{mol/mol}$$

$$x_{NMHC} = 145.6 - 0.970 \cdot 18.9 - 1.1$$

$$x_{NMHC} = 126.2 \mu\text{mol/mol}$$

(4) If the result of paragraph (b)(2) or (3) of this section is greater than the result of paragraph (b)(1) of this section, use the value calculated under paragraph (b)(1) of this section.

**§ 1065.665 THCE and NMHCE determination.**

(a) If we require you to determine THCE, consider references to NMHC and NMHCE in this section to mean THC and THCE, respectively. If we require you to determine NMHCE, first determine NMHC as described in § 1065.660.

$$x_{COmeas} = 29.0 \mu\text{mol/mol}$$

$$x_{H_2OCOmeas} = 8.601 \mu\text{mol/mol}$$

$$x_{H_2O} = 34.4 \mu\text{mol/mol}$$

$$C_{mol} = 1000 \mu\text{mol/mol}$$

$$x_{CO} = 29.0 \cdot \left[ \frac{1 - \frac{34.04}{1000}}{1 - \frac{8.601}{1000}} \right]$$

$$x_{CO} = 28.3 \mu\text{mol/mol}$$

**§ 1065.660 THC and NMHC determination.**

(a) *THC determination.* If we require you to determine THC emission, calculate  $x_{THC}$  using the initial THC contamination concentration  $x_{THCinit}$  from § 1065.520 as follows:

$$x_{THC} = x_{THCinit}$$

Example:

$$x_{THC} = 150.3 \mu\text{mol/mol}$$

$$x_{THCinit} = 1.1 \mu\text{mol/mol}$$

$$x_{THC} = 150.3 - 1.1$$

$$x_{THC} = 149.2 \mu\text{mol/mol}$$

(b) *NMHC determination.* Use one of the following to determine NMHC emission,  $x_{NMHC}$

(1) If you did not measure CH<sub>4</sub>, you may report  $x_{NMHC}$  as  $0.98 \cdot x_{THC}$ .

(2) For nonmethane cutters, calculate  $x_{NMHC}$  using the nonmethane cutter's penetration fractions (PF) of CH<sub>4</sub>, and C<sub>2</sub>H<sub>6</sub>, from § 1065.331, and using the initial NMHC contamination concentration  $x_{NMHCinit}$  from § 1065.520 as follows:

(b) If you measured an oxygenated hydrocarbon's mass concentration (per mole of exhaust), then first calculate its molar concentration by dividing its mass concentration by the molar mass of the oxygenated hydrocarbon.

(c) Then multiply each oxygenated hydrocarbon's molar concentration by its respective number of carbon atoms per molecule. Add these carbon-equivalent molar concentrations to the molar concentration of NMHC. The result is the molar concentration of NMHCE.

(d) For example, if you measured ethanol (C<sub>2</sub>H<sub>5</sub>OH) and methanol (CH<sub>3</sub>OH) as molar concentrations, and acetaldehyde (C<sub>2</sub>H<sub>4</sub>O) and formaldehyde (HCHO) as mass concentrations, you

Example:

$$x_{THC} = 150.3 \mu\text{mol/mol}$$

$$x_{CH_4} = 20.5 \mu\text{mol/mol}$$

$$PF_{CH_4} = 0.980$$

$$PF_{C_2H_6} = 0.050$$

$$x_{NMHCinit} = 1.1 \mu\text{mol/mol}$$

$$x_{NMHC} = \frac{0.980 \cdot 150 - 20}{0.980 - 0.050} - 1.1$$

(3) For a gas chromatograph, calculate  $x_{NMHC}$  using the THC analyzer's response factor (RF) CH<sub>4</sub>, from § 1065.366, and using the initial NMHC contamination concentration  $x_{NMHCinit}$  from § 1065.520 as follows:

$$x_{NMHC} = x_{THC} - RF_{CH_4} \cdot x_{CH_4} - x_{NMHCinit}$$

Example:

$$x_{THC} = 145.6 \mu\text{mol/mol}$$

$$x_{CH_4} = 18.9 \mu\text{mol/mol}$$

would determine NMHCE emissions as follows:

$$x_{\text{NMHCE}} = x_{\text{NMHC}} + \sum_{i=1}^N x_{\text{OHC}_i}$$

$$x_{\text{OHC}_i} = \frac{M_{\text{exhOHC}_i}}{M_{\text{OHC}_i}}$$

Example:

$$x_{\text{NMHC}} = 127.3 \text{ } \mu\text{mol/mol}$$

$$x_{\text{C}_2\text{H}_5\text{OH}} = 100.8 \text{ } \mu\text{mol/mol}$$

$$x_{\text{CH}_3\text{OH}} = 25.5 \text{ } \mu\text{mol/mol}$$

$$M_{\text{exhC}_2\text{H}_4\text{O}} = 0.841 \text{ mg/mol}$$

$$M_{\text{exhHCHO}} = 39.0 \text{ } \mu\text{g/mol}$$

$$M_{\text{C}_2\text{H}_4\text{O}} = 44.05256 \text{ g/mol}$$

$$M_{\text{HCHO}} = 30.02598 \text{ g/mol}$$

$$x_{\text{C}_2\text{H}_4\text{O}} = \frac{0.841}{44.05256} \times 1000 = 19.1 \text{ } \mu\text{mol/mol}$$

$$x_{\text{HCHO}} = \frac{39}{30.02598} = 1.3 \text{ } \mu\text{mol/mol}$$

$$x_{\text{NMHCE}} = 127.3 + 2 \times 100.8 + 25.5 + 2 \times 19.1 + 1.3 = 393.9 \text{ } \mu\text{mol/mol}$$

#### § 1065.667 Dilution air background emission correction.

(a) *General.* To determine the mass of background emissions to subtract from a diluted exhaust sample, first determine the total flow of dilution air,  $n_{\text{dil}}$ , over the test interval. This may be a measured quantity or a quantity calculated from the diluted exhaust flow and the flow-weighted average fraction of dilution air in diluted exhaust,  $\overline{DF}$ . Multiply the total flow of dilution air by the mean concentration of a background emission,  $\bar{x}_{\text{dil}}$ . This may be a time-weighted mean or a flow-weighted mean (e.g. a proportionally sampled background). The product of  $n_{\text{dil}}$  and  $\bar{x}_{\text{dil}}$  is the total amount of a background emission. If this is a molar quantity, convert it to a mass by multiplying it by its molar mass,  $M$ . The result is the mass of the background emission,  $m$ . In the case of PM, where the mean PM concentration is already in units of mass per mole of sample,  $\overline{M}_{\text{PM}}$ , simply multiply the total amount of dilution air by  $\overline{M}_{\text{PM}}$ . The result is the total background mass of PM,  $m_{\text{PM}}$ . Subtract the total background mass from the total mass to correct for background emissions.

(b) You may determine the total flow of dilution air by a direct flow

measurement. In this case calculate the total mass of background as described in § 1065.650(b), using the dilution air flow,  $n_{\text{dil}}$ . Subtract the background mass from the total mass. Use the result in brake-specific emissions calculations.

(c) You may determine the total flow of dilution air from the total flow of diluted exhaust and a chemical balance of the fuel, intake air and exhaust as described in § 1065.655. In this case calculate the total mass of background as described in § 1065.650(b), using the total flow of diluted exhaust,  $n_{\text{dexh}}$ . Then multiply this result by the flow-weighted average fraction of dilution air in diluted exhaust,  $\overline{DF}$ . Calculate  $\overline{DF}$  using flow-weighted average concentrations of emissions in the chemical balance, as described in § 1065.655. You may assume that your engine operates stoichiometrically, even if it is a lean-burn engine, such as a compression-ignition engine. Note that for lean-burn engines this assumption could result in an error in emissions calculations. This error could occur because the chemical balances in § 1065.655 correct excess air passing through a lean-burn engine as if it was dilution air. If an emission concentration expected at the standard

is about 100 times its dilution air background concentration, this error is negligible. However, if an emission concentration expected at the standard is similar to its background concentration, this error could be significant. If you are concerned about this error, we recommend that you remove background emissions from dilution air by HEPA filtration, chemical adsorption, or catalytic scrubbing. You might also consider using a partial-flow dilution technique such as a bag mini-diluter, which uses purified air as the dilution air.

(d) The following is an example of using the flow-weighted average fraction of dilution air in diluted exhaust,  $\overline{DF}$ , and the total mass of background emissions calculated using the total flow of diluted exhaust,  $n_{\text{dexh}}$ , as described in § 1065.650(b):

$$M_{\text{bkgnd}} = \overline{DF} M_{\text{bkgnddexh}}$$

$$M_{\text{bkgnddexh}} = M \cdot \bar{x}_{\text{bkgnd}} \cdot n_{\text{dexh}}$$

Example:

$$M_{\text{NO}_x} = 46.0055 \text{ g/mol}$$

$$\bar{x}_{\text{bkgnd}} = 0.05 \text{ } \mu\text{mol/mol}$$

$$n_{\text{dexh}} = 23280.5 \text{ mol}$$

$$\overline{DF} = 0.843$$

$$C_{\text{mol}} = 1000000 \text{ } \mu\text{mol/mol}$$

$$m_{\text{bkgndNO}_x\text{dexh}} = 46.0055 \cdot \frac{0.05}{1000000} \cdot 23280.5$$

$$m_{\text{bkgndNO}_x\text{dexh}} = 0.0536 \text{ g}$$

$$m_{\text{bkgndNO}_x} = 0.843 \cdot 0.0536$$

$$m_{\text{bkgndNO}_x} = 0.0452 \text{ g}$$

#### § 1065.670 NO<sub>x</sub> intake-air humidity correction.

(a) Correct NO<sub>x</sub> concentrations for intake-air humidity after applying all other corrections.

(b) For compression-ignition engines correct for intake-air humidity as follows or develop your own correction, based on good engineering judgment:

$$X_{\text{NO}_x\text{corr}} = X_{\text{NO}_x\text{uncorr}} \cdot (9.953 \cdot X_{\text{H}_2\text{O}} + 0.832)$$

Example:

$$X_{\text{NO}_x\text{uncorr}} = 700.5 \text{ } \mu\text{mol/mol}$$

$$X_{\text{H}_2\text{O}} = 0.022 \text{ mol/mol}$$

$$X_{\text{NO}_x\text{corr}} = 700.5 \cdot (9.953 \cdot 0.022 + 0.832)$$

$$X_{\text{NO}_x\text{corr}} = 736.2 \text{ } \mu\text{mol/mol}$$

(c) For spark-ignition engines you may use the same correction as for compression-ignition engines, or you

may develop your own correction, based on good engineering judgment.

**§ 1065.672 CLD quench check calculations.**

Perform CLD quench check calculations as follows:

(a) Calculate the amount of water in the span gas,  $x_{H_2Ospan}$  assuming complete saturation at the span gas temperature.

(b) Estimate the expected amount of water,  $x_{H_2Oexp}$  in the exhaust you sample

by considering the maximum expected amounts of water in combustion air, in fuel combustion products, and in dilution air if you dilute.

(c) Calculate water quench as follows:

$$\text{quench} = \left( \frac{x_{NOwet}}{x_{NOdry}} \cdot (1 + x_{H_2Ocalc}) - 1 \right) \cdot \frac{x_{H_2Oexp}}{x_{H_2Ocalc}} + \frac{x_{NO,CO_2} - x_{NO,N_2}}{x_{NO,N_2}} \cdot \frac{x_{CO_2exp}}{x_{CO_2meas}}$$

**Example:**

$x_{NOdry} = 1800 \mu\text{mol/mol}$   
 $x_{NOwet} = 1760 \mu\text{mol/mol}$

$x_{H_2Oexp} = 0.03 \text{ mol/mol}$   
 $x_{H_2Ocalc} = 0.017 \text{ mol/mol}$   
 $x_{NO,CO_2} = 1480 \mu\text{mol/mol}$

$x_{NO,N_2} = 1500 \mu\text{mol/mol}$   
 $x_{CO_2exp} = 2.0\%$   
 $x_{CO_2meas} = 3.0\%$

$$\text{quench} = \left( \frac{1760}{1800} \cdot (1 + 0.017) - 1 \right) \cdot \frac{0.03}{0.017} + \frac{1480 - 1500}{1500} \cdot \frac{2.0}{3.0}$$

$$\text{quench} = -0.0099 - 0.0089 = -1.88\%$$

**§ 1065.690 PM sample media buoyancy correction.**

(a) *General.* Correct PM sample media for their buoyancy in air if you weigh them on a balance. The buoyancy correction depends on the sample media density, the density of air, and the density of the calibration weight used to calibrate the balance. The buoyancy correction does not account for the buoyancy of the PM itself because the mass of PM typically accounts only for (0.01 to 0.10)% of the total weight. A correction to this small fraction of mass would be at the most (0.001 to 0.010)%.

(b) *PM sample media density.* Different PM sample media have

different densities. Use the known density of your sample media, or use one of the densities for some common sampling media:

(1) For PTFE coated borosilicate glass, use a sample media density: 2300 kg/m<sup>3</sup>.

(2) For PTFE membrane (film) media with an integral support ring of polymethylpentene that accounts for 95% of the media mass, use a sample media density: 920 kg/m<sup>3</sup>.

(c) *Air density.* Because a PM balance environment must be tightly controlled to an ambient temperature of (22 ± 1) °C and a dewpoint of (9.5 ± 1) °C, air density is only a function of barometric pressure for this correction.

(d) *Calibration weight density.* Use the stated density of the material of your metal calibration weight. The example calculation in this section uses a density of 8000 kg/m<sup>3</sup>, but you should know the density of your weight from the calibration weight supplier or the balance manufacturer if it is an internal weight.

(e) *Correction calculation.* Buoyancy correct PM sample media using the following:

$$m_{\text{corr}} = m_{\text{uncorr}} \cdot \left[ \frac{1 - \frac{\rho_{\text{air}}}{\rho_{\text{weight}}}}{1 - \frac{\rho_{\text{air}}}{\rho_{\text{media}}}} \right]$$

$$\rho_{\text{air}} = \left( \frac{M_{\text{air}}}{R \cdot T_{\text{amb}}} \right) \cdot p_{\text{barom}} - \left( \frac{p_{H_2O}}{R \cdot T_{\text{amb}}} \right) \cdot (M_{\text{air}} - M_{H_2O})$$

$$@ T_{\text{amb}} = 22 \text{ } ^\circ\text{C}, T_{\text{dew}} = 9.5 \text{ } ^\circ\text{C}, p_{\text{barom}} / \text{kPa}$$

$$\rho_{\text{air}} = (1.1803 \cdot 10^{-2} \cdot p_{\text{barom}}) - 5.2922 \cdot 10^{-3}$$

**Example:**

$$m_{\text{uncorr}} = 100.0000 \text{ mg}$$

$$\rho_{\text{barom}} = 101.325 \text{ kPa}$$

$$\rho_{\text{weight}} = 8000 \text{ kg/m}^3$$

$$\rho_{\text{media}} = 920 \text{ kg/m}^3$$

$$\rho_{\text{air}} =$$

$$(1.1803 \cdot 10^{-2} \cdot 101.325) - 5.2922 \cdot 10^{-3}$$

$$(1.1803 \cdot 10$$

$$-2 \cdot 101.325) - 5.2922 \cdot 10^{-3}$$

$$\rho_{\text{air}} = 1.1906 \text{ kg/m}^3$$

$$m_{\text{corr}} = 100.0000 \cdot \left[ \frac{1 - \frac{1.1906}{8000}}{1 - \frac{1.1906}{920}} \right]$$

$$m_{\text{corr}} = 100.1147 \text{ mg}$$

**§ 1065.695 Data requirements.**

(a) To determine the information we require from engine tests, refer to the standard-setting part and request from your Designated Compliance Officer the application format for certification. We may require different information for different purposes such as for certification applications, alternate procedure approval requests, selective enforcement audits, laboratory audits, production-line test reports, and field-test reports.

(b) See the standard-setting part and § 1065.25 regarding recordkeeping.

(c) We may ask you the following about your testing:

(1) What approved alternative procedures did you use? For example:

(i) Partial-flow dilution for proportional PM.

(ii) CARB test procedures.

(iii) ISO test procedures.

(2) What laboratory equipment did you use? For example, the make, model, and description of the following:

(i) Engine dynamometer and operator demand.

(ii) Probes, dilution, transfer lines, and sample preconditioning components.

(iii) Batch storage media (e.g., bag material, PM filter material).

(3) What measurement instruments did you use? For example, the make, model, and description of the following:

(i) Speed, torque instruments.

(ii) Flow meters.

(iii) Gas analyzers.

(iv) PM balance.

(4) When did you conduct calibrations and performance checks and what were the results? For example, the dates and results of the following:

(i) Linearity checks.

(ii) Interference checks.

(iii) Response checks.

(iv) Leak checks.

(v) Flow meter checks.

(5) What engine did you test? For example, the following:

(i) Manufacturer.

(ii) Family name on engine label.

(iii) Model.

(iv) Model year.

(v) Identification number.

(6) How did you prepare and configure your engine for testing? For example, the following:

(i) Service accumulation; dates, hours, duty cycle and fuel.

(ii) Scheduled maintenance; dates and description.

(iii) Unscheduled maintenance; dates and description.

(iv) Intake restriction allowable pressure range.

(v) Charge air cooler volume.

(vi) Charge air cooler outlet temperature, specified engine conditions and location of temperature measurement.

(vii) Exhaust restriction allowable pressure range.

(viii) Fuel temperature and location of measurement.

(ix) Any aftertreatment system configuration and description.

(x) Any crankcase ventilation configuration and description (e.g., open, closed, PCV, crankcase scavenged).

(7) How did you test your engine? For example:

(i) Constant speed or variable speed.

(ii) Mapping procedure: step or sweep.

(iii) Continuous or batch sampling for each emission.

(iv) Raw or dilute; any dilution air background sampling.

(v) Duty cycle and test intervals.

(vi) Cold-start, hot-start, warmed-up running.

(vii) Intake and dilution air absolute pressure, temperature, dewpoint.

(viii) Simulated engine loads, curb idle transmission torque value.

(ix) Warm idle speed value, any enhanced idle speed value.

(x) Simulated vehicle signals applied during testing.

(xi) Bypassed governor controls during testing.

(xii) Date, time, and location of test (e.g., dynamometer laboratory identification).

(xiii) Cooling medium for engine and charge air.

(xiv) Operating temperatures: coolant, head, block.

(xv) Full names of engine operators and laboratory operators.

(xvi) Natural or forced cool-down and cool-down time.

(xvii) Cannister loading.

(8) How did you validate your testing? For example, results from the following:

(i) Duty cycle regression statistics for each test interval.

(ii) Proportional sampling.

(iii) Drift.

(iv) Reference PM sample media in PM-stabilization environment.

(9) How did you calculate results? For example, results from the following:

(i) Drift correction.

(ii) Noise correction.

(iii) "Dry-to-wet" correction.

(iv) NMHC CH<sub>4</sub> and contamination correction.

(v) NO<sub>x</sub> humidity correction.

(vi) Brake-specific emission formulation: total mass divided by total work, mass rate divided by power, or ratio of mass to work.

(vii) Rounding emission results.

(10) What were the results of your testing? For example:

(i) Maximum mapped power and speed at maximum power.

(ii) Maximum mapped torque and speed at maximum torque.

(iii) For constant-speed engines: no-load governed speed.

(iv) For constant-speed engines: test torque.

(v) For variable-speed engines: test speed.

(vi) Speed versus torque map.

(vii) Speed versus power map.

(viii) Duty cycle and test interval brake-specific emissions.

(ix) Brake-specific fuel consumption.

(11) What fuel did you use? For example:

(i) Fuel that met specifications of subpart H of this part.

(ii) Alternative fuel.

(iii) Oxygenated fuel.

(12) How did you field test your engine? For example:

(i) Data from paragraphs (c)(1), (3), (4), (5), and (9) of this section.

(ii) Probes, dilution, transfer lines, and sample preconditioning components.

(iii) Batch storage media (e.g., bag material, PM filter material).

(iv) Continuous or batch sampling for each emission.

(v) Raw or dilute; any dilution air background sampling.

(vi) Cold-start, hot-start, warmed-up running.

(vii) Intake and dilution air absolute pressure, temperature, dewpoint.

(viii) Curb idle transmission torque value.

(ix) Warm idle speed value, any enhanced idle speed value.

(x) Date, time, and location of test (e.g., dynamometer laboratory identification).

(xi) Proportional sampling validation.

(xii) Drift validation.

(xiii) Operating temperatures: coolant, head, block.

(xiv) Full name of vehicle operator.

(xv) Full names of field test operators.

(xvi) Vehicle make, model, model year, identification number.

#### Subpart H—Engine Fluids, Test Fuels, and Analytical Gases

##### § 1065.701 General requirements for test fuels.

(a) For all emission tests, use test fuels meeting the specifications in this subpart unless the standard-setting part directs otherwise. If we do not specify a service-accumulation fuel for a test engine, use a fuel typical of what you would expect the engine to use in service.

(b) If you produce engines that can run on a type of fuel (or mixture of fuels) that we do not specify in this subpart, you must get our approval to test with fuel representing commercially available fuels of that type. We must approve your fuel specifications before you start testing.

(c) You may use a test fuel other than those we specify in this subpart if you do all the following:

(1) Show that it is commercially available.

(2) Show that your engines will use only the designated fuel in service.

(3) Show that operating the engines on the fuel we specify would increase emissions or decrease durability.

(4) Get our written approval before you start testing.

(d) We may allow you to use a different test fuel (such as California Phase 2 gasoline) if you show us that using it does not affect your ability to comply with all applicable emission standards.

##### § 1065.703 Distillate diesel fuel.

(a) Distillate diesel fuels for testing must be clean and bright, with pour and

cloud points adequate for proper engine operation.

(b) There are three grades of #2 diesel fuel specified for use as a test fuel. See the standard-setting part to determine which grade to use. If the standard-setting part does not specify which grade to use, use good engineering

judgment to select the grade that represents the fuel on which the engines will operate in use. The three grades are specified in Table 1 of this section.

(c) You may use the following nonmetallic additives with distillate diesel fuels:

(1) Cetane improver.

- (2) Metal deactivator.
- (3) Antioxidant, dehazer.
- (4) Rust inhibitor.
- (5) Pour depressant.
- (6) Dye.
- (7) Dispersant.
- (8) Biocide.

TABLE 1 OF § 1065.703.—TEST FUEL SPECIFICATIONS FOR DISTILLATE DIESEL FUEL

| Item  | Units | Ultra low sulfur                                    | Low sulfur  | High sulfur   | Reference procedure <sup>1</sup> |
|---|-------|---|---|---|----------------------------------|
| Cetane Number   | —     | 40–50 ...   | 40–50 ...   | 40–50 .....   | ASTM D 613–03b                   |
| Distillation range:<br>Initial boiling point<br>10 pct. point<br>50 pct. point<br>90 pct. point<br>Endpoint | °C    | 171–204<br>204–238<br>243–282<br>293–332<br>321–366 | 171–204<br>204–238<br>243–282<br>293–332<br>321–366 | 171–204 ...<br>204–238 ...<br>243–282 ...<br>293–332 ...<br>321–366 ... | ASTM D 86–03.                    |
| Gravity   | °API  | 32–37 ...   | 32–37 ...   | 32–37 .....   | ASTM D 287–92.                   |
| Total sulfur  | mg/kg | 7–15 .....  | 300–500   | 2000–4000   | ASTM D 2622–03.                  |
| Aromatics, minimum. (Remainder shall be paraffins, naphthalenes, and olefins)                               | g/kg  | 100 .....   | 100 .....   | 100 .....   | ASTM D 5186–03.                  |
| Flashpoint, min.  | °C    | 54 .....  | 54 .....  | 54 .....  | ASTM D 93–02a.                   |
| Viscosity   | cSt   | 2.0–3.2   | 2.0–3.2   | 2.0–3.2 .....   | ASTM D 445–03.                   |

<sup>1</sup> All ASTM standards are incorporated by reference in § 1065.1010.

§ 1065.705 Residual fuel. [Reserved]

§ 1065.710 Gasoline.

(a) Gasoline for testing must have octane values that represent

commercially available fuels for the appropriate application.

(b) There are two grades of gasoline specified for use as a test fuel. If the standard-setting part requires testing with fuel appropriate for low

temperatures, use the test fuel specified for low-temperature testing. Otherwise, use the test fuel specified for general testing. The two grades are specified in Table 1 of this section.

TABLE 1 OF § 1065.710.—TEST FUEL SPECIFICATIONS FOR GASOLINE

| Item   | Units                           | General testing                                       | Low temperature testing                             | Reference procedure <sup>1</sup> |
|--|---------------------------------|---|---|----------------------------------|
| Distillation Range:<br>Initial boiling point<br>10% point<br>50% point<br>90% point<br>End point | °C                              | ≥ 24–35<br>49–57<br>93–110<br>149–163<br>Maximum, 213 | 24–36<br>37–48<br>82–101<br>158–174<br>Maximum, 212 | ASTM D 86–01.                    |
| Hydrocarbon composition:<br>1. Olefins<br>2. Aromatics<br>3. Saturates                           | µm <sup>3</sup> /m <sup>3</sup> | Maximum, 100,000<br>Maximum, 350,000<br>Remainder     | Maximum, 175,000<br>Maximum, 304,000<br>Remainder   | ASTM D 1319–02.                  |
| Lead (organic)   | g/liter                         | Maximum, 0.013  | Maximum, 0.013                                      | ASTM D 3237–97.                  |
| Phosphorous  | g/liter                         | Maximum, 0.0013                                       | Maximum, 0.005                                      | ASTM D 3231–02.                  |
| Total sulfur   | mg/kg                           | Maximum, 80   | Maximum, 80   | ASTM D 1266–98.                  |
| Volatility (Reid Vapor Pressure)   | kPa                             | <sup>2,3</sup> 60.0–63.4                              | 77.2–81.4   | ASTM D 323–99a.                  |

<sup>1</sup> All ASTM standards are incorporated by reference in § 1065.1010.

<sup>2</sup> For testing at altitudes above 1 219 m, the specified volatility range is (52 to 55) kPa and the specified initial boiling point range is (23.9 to 40.6) °C.

<sup>3</sup> For testing unrelated to evaporative emissions, the specified range is (55 to 63) kPa.

§ 1065.715 Natural gas.

(a) Natural gas for testing must meet the specifications in the following table: