Populations, Activity and Emissions of Diesel Nonroad Equipment in EPA Region 7

BSFC Calculation Methodology Appendix AD

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To determine brake-specific emissions at a point in time (actually a one-second interval) and engine speed (or RPM), N, during the test, we first determine the engine output power, $Power_{actual}$ (N), at that point in time. The engine output power is the maximum power, $Power_{max}$ (N), times the percent load demand, Load (N), that is,

$$Power_{actual}(N) = Power_{max}(N) * Load(N) \qquad \textbf{[eqn 1]}$$

Because most of the measurements did not include engine control unit data the engine speed, N, and percent load, Load(N), or actual engine power, $Power_{actual}$ (N), needed to be estimated. In most cases the data measured were limited to gaseous emissions and exhaust flow rates. From these however, the actual fuel rate, $FuelRate_{actual}$(N) , could be estimated from a carbon balance[1-4]

$$FuelRate_{actual}(N) = (\{[CO_2]_{exhaust} – [CO_2]_{ambient}\} *MW_{CO2}+ [CO]*MW_{CO} + [HC_1]* MW_{HC}) * m_{exhaust} / MW_{exhaust} \qquad \textbf{[eqn 2]}$$

where $[CO_2]_{exhaust}$, $[CO_2]_{ambient}$, [CO], and $[HC_1]$ are the measured exhaust CO_2 and ambient CO_2, CO, and hydrocarbon concentrations, MW_{CO2}, MW_{CO}, MW_{HC}, and $MW_{exhaust}$ are the molecular weights of CO_2, CO, H_1C, and the exhaust gas, respectively, and $m_{exhaust}$, is the reported exhaust mass flow. The vehicle fuel rate can also be expressed explicitly in terms of the power demand on the engine[5-14],

$$FuelRate = \frac{1}{LHV} \bullet \left(\frac{k \bullet N \bullet V_d}{2000} + P/\eta_i \right) \qquad \textbf{[eqn 3]}$$

which includes the vehicle tractive power, P, engine friction, $kNV_d/2000$, indicated efficiency, η_i, and the lower heating value of the fuel, LHV. In this relationship k is the average piston speed, S_p, and engine speed, N, dependent engine friction[15,16],

$$k = k_0 + k_1 N + k_2 \overline{S}_p^2 \qquad \textbf{[eqn 4]}$$

At maximum power the fuel rate is expected to be at its maximum, and the ratio of the fuel rate at maximum power to the maximum power, Pmax, is referred to as the brake specific fuel consumption (bsfc)

$$bsfc(N) = FuelRate_{max}(N) / P_{max}(N). \qquad \textbf{[eqn 5]}$$

Using the above relationships for fuel rate and power,

$$
\frac{FuelRate}{FuelRate_{\max}} = \frac{\dfrac{1}{LHV}\bullet\left(\dfrac{k\bullet N\bullet V_d}{2000}+{P}\big/{\eta_i}\right)}{\dfrac{1}{LHV}\bullet\left(\dfrac{k\bullet N\bullet V_d}{2000}+{P_{\max}}\big/{\eta_i}\right)} = \frac{\left(\dfrac{k\bullet N\bullet V_d}{2000}+{P}\big/{\eta_i}\right)}{\left(\dfrac{k\bullet N\bullet V_d}{2000}+{P_{\max}}\big/{\eta_i}\right)} = \frac{\left(\dfrac{\eta_i k\bullet N\bullet V_d}{2000}+P\right)}{\left(\dfrac{\eta_i k\bullet N\bullet V_d}{2000}+P_{\max}\right)}
$$

$$
= \frac{\dfrac{\eta_i k\bullet N\bullet V_d}{2000}}{\left(\dfrac{\eta_i k_{\max}\bullet N\bullet V_d}{2000}+P_{\max}\right)} + \frac{P}{\left(\dfrac{\eta_i k_{\max}\bullet N\bullet V_d}{2000}+P_{\max}\right)}
$$

$$
= \frac{\dfrac{\eta_i k\bullet N\bullet V_d}{2000}}{P_{\max}\left(1+\dfrac{\eta_i k_{\max}\bullet N\bullet V_d}{2000\ P_{\max}}\right)} + \frac{P}{P_{\max}\left(1+\dfrac{\eta_i k_{\max}\bullet N\bullet V_d}{2000\ P_{\max}}\right)}
$$

$$
\begin{aligned}
&= \frac{\eta_i k\bullet N\bullet V_d}{2000\ P_{\max}}\left(1-\frac{\eta_i k_{\max}\bullet N\bullet V_d}{2000\ P_{\max}}+\left(\frac{\eta_i k_{\max}\bullet N\bullet V_d}{2000\ P_{\max}}\right)^2-\left(\frac{\eta_i k_{\max}\bullet N\bullet V_d}{2000\ P_{\max}}\right)^3+\ldots\right)+ \\
&\frac{P}{P_{\max}}\left(1-\frac{\eta_i k_{\max}\bullet N\bullet V_d}{2000\ P_{\max}}+\left(\frac{\eta_i k_{\max}\bullet N\bullet V_d}{2000\ P_{\max}}\right)^2-\left(\frac{\eta_i k_{\max}\bullet N\bullet V_d}{2000\ P_{\max}}\right)^3+\ldots\right) \\
&\approx \frac{P}{P_{\max}}\left(1-\frac{\eta_i k_{\max}\bullet N\bullet V_d}{2000\ P_{\max}}\right)+\frac{\eta_i k\bullet N\bullet V_d}{2000\ P_{\max}} \\
&= \frac{P}{P_{\max}}+\frac{\eta_i k\bullet N\bullet V_d}{2000\ P_{\max}}\left(k-\frac{P}{P_{\max}}k_{\max}\right)
\end{aligned}
\qquad \textbf{[eqn 6]}
$$

The frictional terms for a diesel engine are on the order of 5 to 15% of the total engine load depending on the engine speed and load[14-16]. In this approximation the engine friction contribution , i.e.,

$$
\left(k-\frac{P}{P_{\max}}k_{\max}\right)\times\left(\frac{\eta_i k_{\max}\bullet N\bullet V_d}{2000}\right)\Big/P_{\max} \qquad \textbf{[eqn 7]}
$$

will be less than 15% and will have the greatest values near the minimum load points. Hence, to calculate brake specific emissions the approximation

$FuelRate(N) / FuelRate_{max}(N) \approx P(N) / P_{max}(N)$ **[eqn 8]**

or

$P(N) \approx FuelRate_{actual}(N)$ ***** $[P_{max}(N) / FuelRate_{max}(N)]$ **[eqn 9]**

$= FuelRate_{actual}(N) / BSFC_{max}(N)$

is used to estimate the vehicle engine power where $FuelRate_{actual}(N)$ is the actual amount of fuel used at engine speed N, both obtained from SEMTECH output.

The Semtech FuelRate(N) output is in units of gal/sec which is converted to grams/second. The conversion uses the following constants: Density H_2O @ 70 F = 62.3 lbm/ft^3, 1 ft^3 = 7.481 gal, 1 lbm = 0.4536 kg, SG=0.85. So the overall conversion constant is 62.3*0.4536*1000*0.85 / 7.481 = 3210.85 g/gal. Because the BSFC units are typically in g/kW-hr and the fuel rate is in units of g/s there is an additional conversion factor needed. That conversion factor is 3600 s/hour.

$Power_{actual}$ (N) = $FuelRate_{actual}$ (N) [g/s] * 3600 / $BSFC_{max}$ (N) [g/kW-hr] **[eqn 10]**

To calculate the brake-specific mass emissions over a specified period of time the work done by the engine must be determined. At each sample interval of Δt_i = 1 second, the work done by the engine is

$$Work_{actual,i} = Power_{actual,i}(N) \times \Delta t_i \quad \textbf{[eqn 11]}$$

From this the total work over the test can be calculated by summing over all test times,

$$Work_{test\,total} = \left(\sum_{all\,test\,sample\,times,\,i} Work_{actual,i}(N) \right) \quad \textbf{[eqn 12]}$$

Substituting in equation 11, yields the total work done during a test in terms of the engine power at each test interval,

$$Work_{test\,total} = \left(\sum_{all\,test\,sample\,times,\,i} Power_{actual,i}(N) \times \Delta t_i \right) \quad \textbf{[eqn 13]}$$

The units of choice for work, is [kW-hr] and as mentioned above the sample times are all, Δt_i =1 second. So to get the work in terms of [kW-hr] a factor of 1hour / 3600 seconds must be included. That is,

$$Work_{test\,total}[kW-hr] = \left(\sum_{all\,test\,sample\,times,\,i} Power_{actual,i}(N) \times \Delta t_i \right) \times \frac{1[\sec ond]}{3600[\sec onds/hour]} \quad \textbf{[eqn 14]}$$

Similarly, the cumulative gaseous emissions in unit of grams over the test are calculated as:

$$Emissions_{test\,total} = \left(\sum_{all\,test\,sample\,times,\,i} Emissions_{actual,i}(N) \times \Delta t_i \right) \quad \textbf{[eqn 15]}$$

where each $Emissions_{actual,\,i}$(N) is a 1 hz emission value at engine speed, N, and time interval, Δt_i, obtained from the SEMTECH output. The SEMTECH software also calculates 1hz time resolved brake specific emissions in units of g/ kW-hr. The work-equivalent (brake-specific) emissions over a given test are thus

$Emissions_{brake\ specific}$ [grams/kW-hr] = $Emissions_{test\ total}$ / $Work_{test\ total}$ **[eqn 16]**

For particulate matter (PM) mass emissions, the value for the test total mass, $m^{filter}_{test\,total}$, is collected in aggregate, i.e., on a filter, but must be corrected for partial sampling and dilution over the specified period of time. The filter mass, $m_{test\,total}^{filter}$, is the post-test minus the pre-test filter mass difference which is measured in the laboratory on a gravimetric scale[17]. From the test measurements, the vehicle exhaust test total PM mass is

$$m_{test\,total}^{exhaust} = \rho_{test\,total}^{exhaust} \times V_{test\,total}^{exhaust} \qquad \textbf{[eqn 17]}$$

where $\rho_{test\,total}^{exhaust}$ is the cumulative exhaust mass concentration or mass density and $V_{test\,total}^{exhaust}$ is the vehicle total test exhaust volume. The test total exhaust PM mass density can be put in terms of the test total filter mass, $m_{test\,total}^{filter}$, and the test total MPS sample volume, $V_{test\,total}^{MPS\,sample}$, as follows

$$\begin{aligned} \rho_{testtotal}^{exhaust} &= \rho_{testtoal}^{MPS\,sample} && \text{since the sample is collected directly from the exhaust} \\ &= m_{testtotal}^{MPS\,sample} / V_{testtotal}^{MPS\,sample} && \\ &= m_{testtotal}^{filter} / V_{testtotal}^{MPS\,sample} && \text{since the filter collects all of the MPS sample volume} \\ & && \text{and all dilution air is HEPA filtered} \end{aligned} \qquad \textbf{[eqn 18]}$$

The test total sample volume, $V_{test\,total}^{MPS\,sample}$, is calculated by summing over all test time the measured MPS sample flow rates, $(\Delta V/\Delta t)_i^{MPS\,sample}$, which are in units of standard cm^3/minute and then applying appropriate conversion factors to get the total test MPS sample volume in units of liters,

$$V_{test\,total}^{MPS\,sample}[L] = \left(\sum_{all\,test\,sample\,times,\,i} (\Delta V/\Delta t)_i^{MPS\,sample} \left[scm^3 / \min ute \right] \times \Delta t_i \, \frac{1000\left[L/cm^3\right]}{60\left[\sec onds/\min ute\right]} \right) \qquad \textbf{[eqn 19]}$$

Similarly, the test total exhaust volume, $V_{test\,total}^{exhaust}$, can be calculated by summing over the individual measured exhaust flow rates, $(\Delta V/\Delta t)_i^{exhaust}$,

$$V_{test\,total}^{exhaust}[m^3] = \left(\sum_{all\,test\,sample\,times,\,i} (\Delta V/\Delta t)_i^{exhaust} \left[sft^3 / \min ute \right] \times \Delta t_i \times 0.0283 \left[m^3 / ft^3 \right] \right) \qquad \textbf{[eqn 20]}$$

Hence, the vehicle exhaust test total PM mass is

$$\begin{aligned} m_{test\,total}^{exhaust} &= \rho_{test\,total}^{exhaust} \times V_{test\,total}^{exhaust} \\ &= \left(m_{test\,total}^{filter} / V_{test\,total}^{MPS} \right) \times V_{test\,total}^{exhaust} \end{aligned} \qquad \textbf{[eqn 21]}$$

And the work-equivalent (brake-specific) emissions are calculated as:

$$m_{test\ total}^{exhaust} / Work_{test\ total}\,[kW\ hr] = \frac{m_{test\ total}^{filter} \times \left(V_{test\ total}^{exhaust} / V_{test\ total}^{MPS} \right)}{Work_{test\ total}[kW\ hr]} \qquad \textbf{[eqn 22]}$$

where the test total work, $Work_{test\ total}$, is given in equation 14.

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