Emissions from Non-Road Mobile Machinery – Focus on Engine Load

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Introduction

In many countries the emissions from non-road mobile machinery (NRMM) constitute a significant fraction of the total emissions to air of regulated pollutants. This applies to NO_X and PM through emissions from diesel engines but also to HC and CO, mainly through emissions from two-stroke spark ignition engines. To exemplify with some numbers from the official national Swedish air emission inventory for the year 2012, the ratios between NRMM and road traffic emissions were 0.32 for NO_X, 0.52 for HC, 1.19 for $PM_{2.5}$ and 0.18 for CO_2. The general knowledge level on emissions from NRMM is much lower than for road traffic. Most emission data are from engine bench studies and it is normally not clarified how well these data represent the actual emissions in real-world operation.

The calculation of fuel consumption from NRMM normally utilises specific fuel consumption factors expressed as mass of fuel consumed per engine output work, e.g. g/kWh. To quantify the actual fuel consumption, these factors are then multiplied by the installed engine power, an engine load factor, LF, and the time the machine is in operation. Thus, the equation used for calculation of fuel consumption of NRMM is typically formulated as:

$$FC = Hr * P * LF * SFC \tag{1}$$

where FC is the fuel consumption in gram [g], Hr is the number of operating hours [h], P is the engine power rating [kW], LF is the engine load factor (dimensionless, a value between 0 and 1) and SFC is the specific fuel consumption [g/kWh].

Correspondingly, the calculation of emissions from NRMM normally utilises emission factors expressed as mass of emission per engine work, e.g. g/kWh. To quantify the actual emissions, these emission factors are then multiplied by the installed engine power, the engine load factor, LF, and the time the machine is in operation. Thus, the equation for estimating the emissions of CO_2, NO_X, etc. is formulated as:

$$E_i = Hr * P * LF * EF_i \tag{2}$$

where E_i is the emission in g of substance *i*, and EF_i is the emission factor stated in the unit g/kWh. The emission factors are usually referenced to the legal levels (Lindgren 2007, Winther and Nielsen 2006, Schäffler and Keller 2008). Further, the emission factor may be adjusted in order to account for machine age, transient operation conditions and fuel quality variations.

Both the SFC and emissions are in many models (e.g., Lindgren 2007, Winther and Nielsen 2006) assumed to be independent of engine load. In reality, however, it is known that the SFC will be higher at low and high loads than at loads for which the engine is optimised and that emissions of other substances will vary with engine load. The model presented by Schäffler and Keller (2008) uses a load dependent SFC.

In this paper we focus on the engine load factor. In estimates of emissions from NRMM the LF must be considered as the most uncertain factor. Typically, values in use today are either estimates from industry experts or are taken from the test cycles used for the emission regulations. The first method will result in a large spread in the data, and for the second method there is normally no clear relation to how the engines in NRMMs are operated during actual use. Further, in many cases it is unclear if the LF values include the idle periods or not. Obviously this will have a large influence on the resulting emission calculations and on what time of operation that should be used in emission calculations. There is a risk that emission inventories use operation hours that include idling and LFs that do not include idling which would give the wrong results. The machines that are in focus for this study are powered by diesel engines with rated power exceeding 37 kWh.

Method

Modern NRMMs often contain systems where the fuel consumption together with several other operational parameters, are monitored continuously. In order to assess the engine load factor, data was collected from the on-board computer systems on a number of different NRMMs from two different manufactures during their actual operation in Sweden during 2013. The data collected comprised the fuel consumption and the time the machine was used split into idle and operation. To get the average LFs, the annual fuel consumption (in litres) was multiplied with the fuel density and divided by the specific fuel consumption; the installed engine power; and the annual operating hours. Data was only available for certain machine types and included idling. In order to calculate the LFs, specific fuel consumption for the engines of 220 – 230 g/kWh was used; the values were obtained from the engine manufacturers; and the diesel fuel density was set to 830 kg/m^3. The maximum rated power (expressed as the ISO net value) for the engines are taken from brochures from the manufacturers.

Results and discussion

Table 1 gives the resulting data for a number of machine types. Note that the idling periods are included when calculating the LFs.

Table 1: Engine power load factor data calculated from measurement values for NRMMs operated in Sweden

Machine type	Engine size class (kW)	Engine power load factor (incl. idle)	Uncertainty (2 s.d.)	# of data
Wheel loader	75-130	0.22	0.04	494
Wheel loader	130-560	0.28	0.05	520
Excavator (crawler)	37-75	0.39	0.09	44
Excavator (crawler)	75-130	0.37	0.06	255
Excavator (crawler)	130-560	0.38	0.10	323
Excavator (wheel)	75-130	0.30	0.05	485
Articulated hauler	130-560	0.23	0.05	75

The values in Table 1 can be compared with values used in different models for computing fuel consumption and emissions from NRMMs. The USEPA non-road model (USEPA, 2010/ NONROAD2008a) use 0.59 for excavators and wheel-loaders which is significantly higher than the data obtained here. Winter and Nielsen (2006) use 0.5 for wheel-loaders and 0.6 for excavators, while Schäffler and Keller (2010) use 0.48 for all the machine types studied here. The data obtained in this work thus indicate that the LFs used in the available models, at least for the machine types in Table 1, are too high. Table 2 gives a summary of the LFs from different models for the machine types where new data are available in this study.

Table 2: Comparison between the LF values obtained in this study to other sources

Machine type	Engine size class (kW)	LF, this work	LF, present Swedish model	LF USEPA (EPA 2010)	LF Winther and Nielsen (2006)	LF (effective) Schäffler and Keller (2008)
Wheel loader	75-130	0.22	0.48	0.59	0.5	0.48
Wheel loader	130-560	0.28	0.48	0.59	0.5	0.48
Excavator (crawler)	37-75	0.39	0.4	0.59	0.6	0.48
Excavator (crawler)	75-130	0.37	0.4	0.59	0.6	0.48
Excavator (crawler)	130-560	0.38	0.4	0.59	0.6	0.48
Excavator (wheel)	75-130	0.30	0.4	0.59	0.6	0.48
Articulated hauler	130-560	0.23	0.21	0.21	0.4	0.48

The new values presented here for the LF for certain machine types are suggested to be of better quality than previously used values. The reason is that they are computed using continuously logged data from a large number of machines while used in different types of real-world operation. For the machine types where no new data is obtained in this study, no changes in the LFs used are suggested.

Table 3: Suggested new LFs

Type	Power range (kW)	LF in present Swedish model	Suggested new value
Wheel loaders	37-130	0.48	0.22
	130-560		0.28
Excavators (crawler)	<37-75	0.4	0.39
	75-130		0.37
	130-560		0.38
Excavators (wheel)	37-560	0.4	0.30
Articulated hauler	75-560	0.21	0.23

Using the load factors in Table 3 when calculating the Swedish NRMM emissions will lead to lower fuel consumption and emissions with about 20%, even though the LFs are only changed for the machine types in Table 3. The reason is that these machine types represent almost 60% of the fuel consumption from NRMM in Sweden. Table 4 shows the emissions of NO_X, PM and CO_2 and the fuel consumption from NRMM in Sweden for 2012 when using the old and the new set of LFs, respectively. There is clearly a large impact on the emissions due to the update of load factors in equations 1 and 2.

Table 4: Swedish emissions from large NRMMs excluding tractors

	Swedish reporting for 2012 (tonne)	**Recalculated with new LFs (tonne)**
Fuel	532 502	426 891
NO_X	8 503	6 853
PM	573	464

The increasing use of automatic tracking and logging of operational data for NRMM will make it possible to extend the presented analysis to an increased number of machine types. The growing stock of data available for analysis will also make it possible to increase the accuracy of the data, differentiate between operational situations (idle, low/medium/high load) and give time and geographical resolution of the emissions (e.g. winter/summer, urban/rural etc.).

References

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