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Tank-to-wheel emissions from articulated steered wheel loaders

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Abstract

Performing a comprehensive emission accounting via monitoring equipment to survey the performance of machinery is often an intensive work and costly. This often requiring hours of measurements and a sufficient number of observations to obtain valid findings. The purpose of current work is to introduce a screening emission accounting as a way to have a quick overview of emissions associated with non-road mobile machinery by having a simplified assessment method. To meet this aim, this study uses documented data from performances of machinery and couples them with the recently published guidebook by the European Emission Agency. To map the results, operational performances of four wheel loaders operating in quarries to move stone materials are used, equipped with Stage IV engines and net power output in a range between $130 \leq kW < 560$. The obtained results showed that the positive correlation between an increase in fuel consumption and exhaust emissions is not changed. The mass of emissions, however, is better addressed if emissions are linked with the efficiency of equipment, instead of effective hour. Machinery that consumed less fuel per m^3 moved volume of materials, resulted in having less emissions compared to those that had higher fuel consumption per m^3 moved volume.

Keywords: construction equipment; non-road mobile machinery; screening emission accounting.

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Nomenclature

ADF adjustment deterioration factor [%]
DF deterioration factor [%]
E mass of emission [g]
ED energy density [g/kg fuel]
EF emission factor [g/kWh]
EH effective hour [eh]
FC fuel consumption per effective hour [l/eh]
LF adjustment load factor [%]
i pollutant type [-]
p power range [kWh]
s technology level [-]
t time [eh]
x machinery type [-]
y fuel type [-]

1. Introduction

Since the global agreements in reduction of anthropogenic greenhouse emissions (United Nations Framework Convention on Climate Change, 2016), the Norwegian government has mandated various climate mitigation measures to advocate the long-term global objective (Norwegian Ministry of Climate and Environment, 2015). In the domain of the transport sector, corresponding for ca. 30% of total GHG emissions in Norway (Ministry of The Environment, 2012), the Norwegian government has developed action plans to help Norway in achieving parts of the mitigation goals in various phases. In the forthcoming of the National Transport Plan (NTP), the Norwegian government aims at reduction of 40% of emission levels from transport infrastructure until 2030 compared with 1990 levels (Ministry of Transport and Communications, 2017). The same report has an ambition to reduce the emissions by 50% from maintenance and rehabilitation of existing road infrastructure. Such strategic actions are mandated partly due to increase in road traffic volume in the last decade (Statistisk sentralbyrå, 2017) and expected in average yearly expansion of the road networks in Norway by 250 km (Granden, Johansen and Bakløkk, 2017).

Emission reduction from machinery has been a discussed topic for years (due to having the highest share of GHG emissions in the transport sector (Ministry of Transport and Communications, 2017)) and thus various measures and standards have implemented to develop cleaner fuels and reduce tailpipe emissions. Since the 1970s, a series of legislative rules and regulations have been set in Europe to assist in emissions reduction and discourage the use of highly polluting equipment (Nesbit *et al.*, 2016). A series of successive machine improvements, done in stages has already led to some emissions reductions. The goal of each stage has been to put certain upper limit emission levels for different machinery categories and types in different power ranges to pave the road for achieving successful emission controls and engine technologies.

Non-road mobile machinery (NRMM) have faced such a tightening of emissions since 1997 (European Parliament, 1997). NRMM, in various types, are used primarily for heavy duty tasks off the road and have applications in various sectors such as manufacturing industry, agriculture, forestry, gardening, construction etc. The main challenges with NRMM, particularly ones equipped with diesel-powered engines, is their high emissions of particulate matters (PM) and Nitric Oxides (NO_x) (Lewis *et al.*, 2009; Fu *et al.*, 2012; Notter and Schmied, 2015; Cao *et al.*, 2016). In addition, the same NRMM can be used in different conditions, which results in having dissimilar ranges of operations and performances due to variations in travel distance, angle of road, soil composition, the driver's skill, and the difficulty of the task (Smith, Wood and Gould, 2000; Bruce *et al.*, 2001, 2001).

Based on recently published research (Barandica *et al.*, 2013; Garbarino *et al.*, 2014; Barati and Shen, 2016; Karlsson *et al.*, 2017), earthworks activities are often found to be among the main contributors in overall GHG emissions and energy consumption of road infrastructure. This means that during the construction phase of road infrastructure and depending on the topography of the terrain and the retained road geometry, the share of GHG emitted from earthworks' activities may be relatively higher compare to that of other components, such as road materials, transportation and road furniture, like guardrails, traffic signs and light poles. However, the conditions under which a particular type of machinery operates and the resulting effects on tailpipe emissions (i.e. tank-to-wheel) requires more investigation. This is due to variations in working conditions and availability of different types and classes of machinery that can carry out work; see, for instance, Lewis et al. (2009; 2012), Fu et al. (2012), Lijewski et al. (2013), Sennoune et al. (2014), Barati and Shen (2016) and Cao et al. (2016).

Gaining insightful knowledge about the existing gaps and bridging them have been of interest for various actors because of variation in operations and costs of different NRMM in different setups. Such information assists authorities in having an intuitive view and taking informed decisions when enforcing different climate policies. It might be also of interest for contractors, especially if climate emissions soon becomes a part of tendering process in road projects (Solem, 2017).

The aim of current paper is to establish baseline emissions (based on a screening method) for a small group of NRMM and use the Norwegian construction machinery database to explain the performance and the emissions dissimilarities within the group during in-use operation. Hence, this paper only focuses on articulated steered wheel loaders equipped with four different nominal power engines. Data on average technology mix performance and effective hours of those machines are then processed and analyzed to drive baseline emissions. In addition, the patterns of the obtained results are investigated further and discussed. The emission accounting in this regard follows the framework of the recently published emissions inventory guidelines, which was jointly developed by the European Environmental Agency (EEA) and European Monitoring and Evaluation Programme (EMEP).

2. Method

Several types and classes of NRMM have been developed for a diverse range of operations (i.e. engine powers and loads) and conditions to carry out work. However, it often happens that operations of a certain type of machines in a certain power range may not be closely similar. This often occurs as a result of variations of environmental factors in addition to workloads under which machinery operates.

The present research work takes a very narrow approach to derive screening emission accounting for few wheel loaders using data from the field (real world data). The data was collected for all the considered equipment, with the assumption of similar operating conditions in Norway. Based on the power ranges of the aggregated data, the baseline emissions are established. The following subsection describes the source of the data used and method employed to calculate emissions.

2.1. Data source for machinery

To quantify potential emissions corresponding to each sub-category of wheel loaders, inventory data compiled in the Norwegian construction machinery database (NTNU and MEF, 2016), were used. The database covers a range of historical data, dating back to 1970s, from various construction projects in Norway. In this study, emissions corresponding to four wheel loaders equipped with rock buckets are examined. The loaders are equipped with diesel reciprocating engines with four different maximum net power outputs. Table 1 illustrates the specification of each machine based on the inventory data.

Table 1. Information of wheel loaders.

	Machine A	Machine B	Machine C	Machine D
Max. net power (kW)	171	206	288	403
Operating weight (ton)	20.5	26.5	31	51.5
Economic lifetime (eh)	7667	8680	9800	13800
Load capacity (m^3/eh)	168	183	198	250
Fuel consumption (l/eh)	39.5	42	46	60
Emission standard	EPA Tier 4 final / EU Stage VI			

This study uses another indication than the annual work hour or operation hours (Lindgren, 2007; Helms and Lambrecht, 2009; Jerksjö, Wisell and Fridell, 2015) to measure the average hourly performance of each machine. The indicator of the choice is effective hour (EH) that represents the time a machine is operated efficiently including both direct production time (i.e. net operation time) and other operational time that is necessary to perform duties (i.e. additional operation time) (Aune, Bruland and Johannessen, 1992). For the case of the wheel loader, the net operation time is when the wheel loader is driven to piles, filling up the bucket, driving to dump trucks and emptying the bucket. But, the additional operation time is the time spent by the wheel loader to trim piles or waited for haul trucks.

Variations of loads substantially affect fuel consumption and generated emissions (Hansson *et al.*, 1998; Lindgren, 2007). NRMM is operated in different conditions and operation loading such that a mobile machine, depending on its tasks, could be run under full or rated loads. Here, the four articulated steered wheel loaders were operated in quarries to move stone materials. The presented load capacity in table 1 refers to moved volume of stone materials over 1 EH in a well-organized operation in quarries. The density of stone materials was taken to be as 2.7 per unit volume (2.7 tons per m^3).

2.2. Data source for emissions

The calculated emission factors (EF) is based on combustion of fuel to power and evaporation. The used method to quantify exhausted gases in explained extensively in EMEP/EEA air pollutant emission inventory guidebook 2016 (Winther *et al.*, 2017) and it quantifies baseline gaseous emissions based on three levels of information.

- Tier 1 estimates emissions based on a single average emission factor per ton of fuel use [g/ton]. The information are macro-level for each type of fuel and each NRMM category, but it does not distinguish between engine technologies.
- Tier 2 is meso-level information and estimates emissions based on fuel type and engine technology, but the emission factors do not differentiate between engine powers. The unit of emission factors in this method is still fuel-based [g/ton].
- Tier 3 estimates emissions based on mass of emitted gases per unit of energy [g/kWh]. This method provides more detailed baseline emission factors compared with the two prior methods, whose estimations rely on aggregated fuel statistics at country and/or regional level.

In this study, the emission factors from the Tier 3 method are used to establish emissions corresponding to wheel loaders.

2.3. Emissions derivations

The following formula is used to calculate baseline emissions corresponding to each gaseous emission during the whole performance lifetime of each wheel loader. This equation only quantifies exhaust gases during the effective hours of each machine.

$$E_{xi} = \sum_{t=0}^{EH} EF_{tpi} \cdot FC_x \cdot ED_{xy} \cdot LF_t \cdot (1 + ADF_{tpi}) \tag{1}$$

Where E is of the calculated amount of pollutant i for construction machinery x in mass unit [g], EF is the baseline emission factor [g/kWh] of pollutant i, FC is fuel consumption of machinery x per effective hour [l/eh], ED is energy density of fuel y burned in machinery x [g/kg fuel], LF is the adjustment load factor as a function of technology levels t and is the portion of utilized engine power during operating conditions (based on the guidebook it is set to 100%) [%] and ADF is the deterioration factor adjustment modifying emissions as the machinery ages [%].

In the equation 1, both EF and ADF are functions of technology levels t [eh] and power ranges p [kWh]. The selected data from the guidebook (Winther *et al.*, 2017) are limited to technology level Stage IV and power range between 130 and 560 kW. Also, this equation quantifies emissions over the economic lifetime of construction machinery x. Table 2 shows the baseline emission factors for diesel NRMM.

CO_2 and SO_2 are predominantly assumed as fuel-driven emissions and not depending on engine type nor equipment technology (Winther *et al.*, 2017) [In spite of the assumptions, the amount of CO_2 will increase if an engine can efficiently oxidize the fuel, also the existence of desulfurization ($DeSO_X$) just like denitogenation ($DeNO_X$) can significantly reduce SO_2 emission]. Since no emission factor is suggested for carbon dioxide and sulfur dioxide by the guidebooks (Winther *et al.*, 2013, 2017), this study uses CO_2 intensity of fuels suggested by Lindgren (2007) that assumed per kilogram of burned fuel, 3146 grams of CO_2 are emitted. This study assumes that diesel fuel contains 10 ppm sulfur and all sulfur in the fuel is transformed fully to sulfur dioxide. Also, it is assumed that the density of diesel is 0.85 kilogram per liter.

Table 2. Emission factors and deterioration factors for diesel NRMM with engine emission standard, Stage IV and within net power range 130-560 kW.

	NH_3	CH_4	BC	$PM/PM_{10}/PM_{2.5}$	N_2O	VOC	NO_X	CO
Emission factors (g/kWh)	0.002	0.003	0.018	0.025	0.035	0.13	0.4	1.5
Deterioration factor (% avg. engine lifetime)	-	0.15‡	-	0.473†	-	0.027†	0.008†	0.151†

‡ Obtained from the emission inventory guidebook (Winther *et al.*, 2013).

† Obtained from the emission inventory guidebook (Winther *et al.*, 2017) and German emission calculation report (Lambrecht *et al.*, 2004).

As machinery ages, the rate of emissions start increasing, owing to engine wear and tear. To quantify the deterioration factor adjustment in equation 1, the following equation is used to capture the increased rate over each effective hour.

$$ADF_{tpi} = \frac{t}{EH} DF_{tpi} \tag{2}$$

Where t is a time-counter and measures the number of effective hours a machine was under duty [eh], EH is the economic lifetime of equipment in the unit of effective hours [eh], and DF is the deterioration factor in the unit of average engine lifetime [%].

In table 2, the deterioration factors obtained from the emission inventory guidebook (Winther *et al.*, 2013), were adjusted to be in the unit of % average engine lifetime. Based on the guidebook (Winther *et al.*, 2013), the degradation factors of diesel engines are calculated in the unit of $\%year^{-1}$ and in the same guidebook it is assumed that an average lifetime of a wheel loader is expected to be about 10 years. To do the adjustment, this study simply multiplied the obtained deterioration factors by 10.

Despite the made adjustment for CH4, this study disregarded the suggested deterioration factors for CO_2, SO_2 and fuel consumption. The guidebook (Winther *et al.*, 2013) assumes that the deterioration factor is 1% for every operation year of machinery. Such consideration was not taken into account as this study uses average fuel consumption over the economic lifetime of machinery and both CO_2 and SO_2 are assumed to be fuel-based emissions (Winther *et al.*, 2013, 2017).

3. Results and discussion

This study used an alternative approach to what has been done by prior studies (Lindgren, 2007; Wetterberg *et al.*, 2007; Jerksjö, Wisell and Fridell, 2015; Notter and Schmied, 2015) and uses liters of fuel consumption per effective hours, instead of using nominal power and operation hours. This action results in having more of an average technology mix approach and not being bonded to know variations of engine speeds within each vehicle, as well as requiring surveying data from many samples. In addition, this study is not required to know for how many years a machine has been in-service (Lindgren, 2007; Notter and Schmied, 2015). Instead, it uses EH, which is based on the economic lifetime of a machine, to measure emissions. Such an approach has an advantage when adjusting the deterioration factor at each effective hour and does not require the knowledge of the average operation hours of a machine in sequential year.

In addition of measuring the exhausted emissions for each machine over their economic lifetime, this study measured emissions per EH of each machine. The calculated emissions are simply based on division of the total emissions from equation 1 by the corresponding economic lifetime of each machine. Table 3 demonstrates the total emissions and emissions per EH. Also, figure 1 illustrates the relative difference between emissions per EH of the wheel loaders.

By looking at the data, particularly emission per EH, the relative emission differences between machines follows somehow a similar pattern when comparing fuel consumption per EH. Meaning that as the fuel consumption per EH between machines increases/decreases with certain percentages, the relative emission traces almost similar percentages of increase/decrease. For instance, the relative increase in fuel consumption per EH is approx. 6.3% by switching from machine A to B and by comparing the mass of the emissions for the two machines similar relativity can be observed.

Table 3. Emissions summary for each of the wheel loader.

Pollutants	Machine A		Machine B		Machine C		Machine D	
	Cumulative emissions (ton)	Emission per EH (g/eh)	Cumulative emissions (ton)	Emission per EH (g/eh)	Cumulative emissions (ton)	Emission per EH (g/eh)	Cumulative emissions (ton)	Emission per EH (g/eh)
SO_2	5.07E-03	6.72E-01	6.10E-03	7.14E-01	7.54E-03	7.82E-01	1.39E-02	1.02E+00
NH_3	6.07E-03	8.04E-01	7.30E-03	8.55E-01	9.03E-03	9.36E-01	1.66E-02	1.22E+00
CH_4	9.78E-03	1.30E+00	1.18E-02	1.38E+00	1.46E-02	1.51E+00	2.67E-02	1.97E+00
BC	5.46E-02	7.24E+00	6.57E-02	7.69E+00	8.13E-02	8.43E+00	1.49E-01	1.10E+01
$PM/PM_{10}/PM_{2.5}$	9.38E-02	1.24E+01	1.13E-01	1.32E+01	1.40E-01	1.45E+01	2.56E-01	1.89E+01
N_2O	1.06E-01	1.41E+01	1.28E-01	1.50E+01	1.58E-01	1.64E+01	2.90E-01	2.14E+01
NO_X	1.22E+00	1.61E+02	1.47E+00	1.72E+02	1.81E+00	1.88E+02	3.33E+00	2.45E+02
VOC	4.00E-01	5.30E+01	4.81E-01	5.63E+01	5.95E-01	6.17E+01	1.09E+00	8.04E+01
CO	4.89E+00	6.48E+02	5.89E+00	6.90E+02	7.28E+00	7.55E+02	1.34E+01	9.85E+02
CO_2	7.97E+02	1.06E+05	9.59E+02	1.12E+05	1.19E+03	1.23E+05	2.18E+03	1.60E+05

However, the relative differences for each pollutant, sometimes it is exactly the same relative difference as the relative fuel consumption per EH and sometimes it is partially similar. This variation in the relative differences is due to the degradation factors corresponding to each pollutant. The relative differences become partially similar as the deterioration factor gets closer to one. The relative emission differences of particulate matters (PM), due to having the highest degradation factor (see table 2), are the least similar to relative fuel consumption per EH. Conversely, the relative differences of ammonia (NH_3), nitrous oxide (N_2O), sulfur dioxide (SO_2), carbon dioxide (CO_2) and black carbon (BC) are exactly the same as the relative fuel consumption per EH due to having no degradation factors [i.e. DF_{tpi} is 0%].

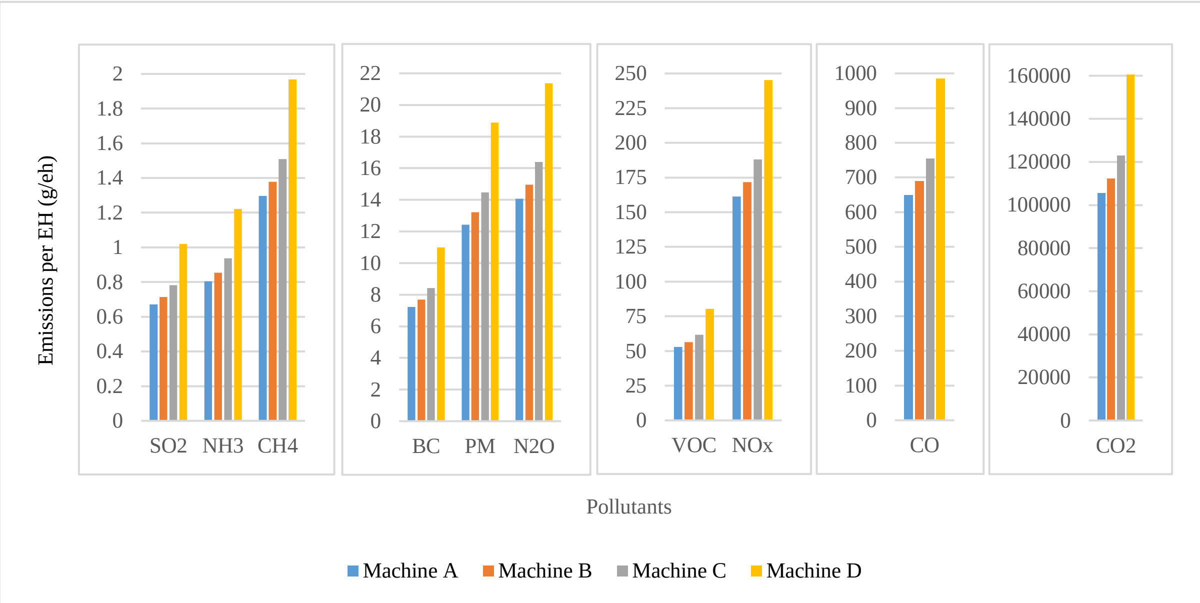

Fig. 1 Schematic comparison of fuel based emissions per economic lifetime for the four wheel loaders, based on table 3.

In addition to the demonstrated results in table 3, this study converts the emission per EH to emission per cubic meter to observe the amount of the emission from each machine based on the load capacity. Such an attempt helps to understand which machine has lower emissions per m^3 moved volume with respect to the cumulative emissions. Table 4 demonstrates emission per m^3 moved volume for each machine. In addition, the results of table 4 is illustrated in figure 2.

Table 4. Comparison of emissions per m^3 moved volume for the wheel loaders.

Pollutants	Machine A Emission per moved volume (g/m3)	Machine B Emission per moved volume (g/m3)	Machine C Emission per moved volume (g/m3)	Machine D Emission per moved volume (g/m3)
SO_2	4.00E-03	3.90E-03	3.95E-03	4.08E-03
NH_3	4.79E-03	4.67E-03	4.73E-03	4.88E-03
CH_4	7.72E-03	7.53E-03	7.62E-03	7.88E-03
BC	4.31E-02	4.20E-02	4.26E-02	4.40E-02
$PM/PM_{10}/PM_{2.5}$	7.40E-02	7.22E-02	7.31E-02	7.55E-02
N_2O	8.37E-02	8.17E-02	8.27E-02	8.55E-02
NO_X	9.61E-01	9.38E-01	9.49E-01	9.81E-01
VOC	3.15E-01	3.08E-01	3.11E-01	3.22E-01
CO	3.86E+00	3.77E+00	3.81E+00	3.94E+00
CO_2	6.29E+02	6.14E+02	6.21E+02	6.42E+02

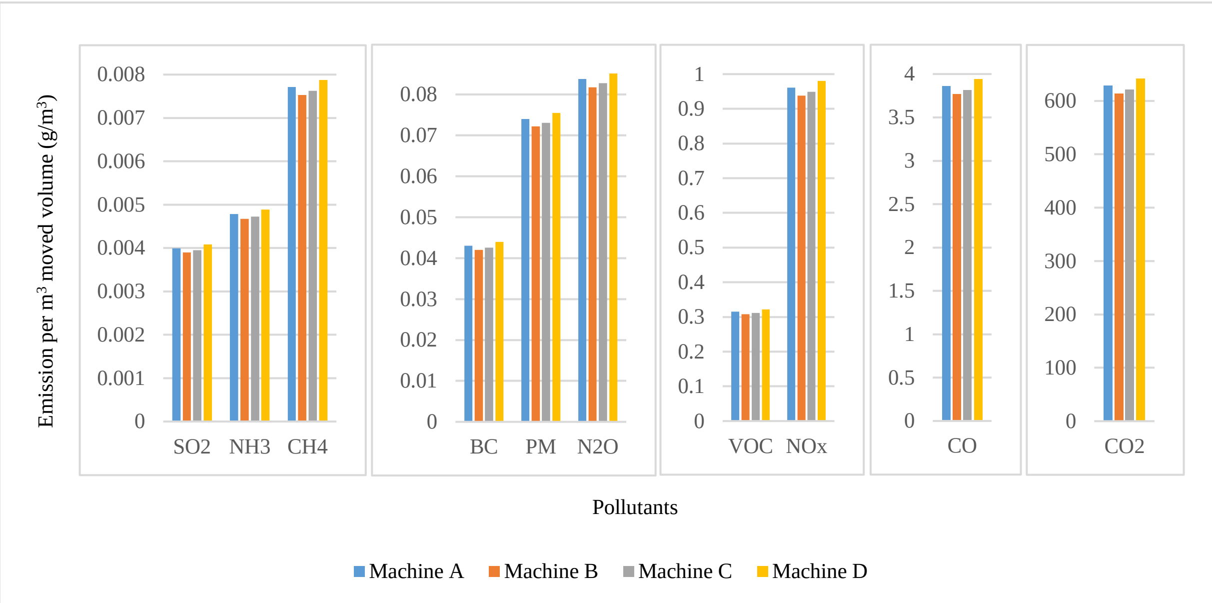

Fig. 2 The influence of load capacity on gaseous emissions, based on table 4.

By looking at the table, some interesting results could be obtained. Despite the lowest fuel consumption per EH and the lowest cumulative emissions corresponding to machine type A, this machine did not show to be the most effective one when it comes to emissions per m^3 moved volume. This comes to the point that the emission results from table 4 are relatively lower for machine B and machine C compared with machine A. Such slightly higher emissions per moved volume for machine A could be due to efficiency of the engine that resulted in having higher fuel consumption per EF. However, there could be some other reasons rather than the efficiency of the engine that resulted in having higher emissions per m^3 moved volume, like the experience of the driver, weather conditions, travelled distances in the working site and tire pressure. This paper was incapable of unveiling the underlying reasons for such behaviours in the table.

4. Limitations

One of the underlying shortcoming of using baseline emission factors in this study is due to the lack of real-word emission data. Such limitation often result in having inconsistence between the used emission factors and emission factors from monitored in-service non-road mobile sources. Portable emission measurement system (PEMS) are found to be a prominent solution in gaining more adequate emission estimations and validating engines performance with emission requirements (Lewis *et al.*, 2009; Fu *et al.*, 2012; Lijewski *et al.*, 2013; Jerksjö, Wisell and Fridell, 2015; Cao *et al.*, 2016). The measured data by PEMS can resolve the current limitation as it measures emissions corresponding to machinery under actual operation conditions, which somewhat differs from the laboratory conditions (Winther *et al.*, 2017). As a point for improvement, it is worth including such data in future research and compare the results with the laboratory data.

Using annual work hour had been introduced by some prior authors (Lindgren, 2007; Wetterberg *et al.*, 2007; Jerksjö, Wisell and Fridell, 2015) to project a clearer picture of a machinery's performance. Annual work hour referred to the number of hours a machine with a particular age profile could be potentially operated effectively over a year. Although utilization of annual work hours help to understand the variation of emissions in different stratified years, this study lacks having such resolution and instead it accounts for operational emissions over the entire economic lifetime of machinery. Inclusion of such information is found to be essential as it has a strong dependency to annual operation time of machinery and the condition under which it performs.

The implemented method in this study was only for a single classification of machines and did not evaluate other classifications. In future research, it is expected to cover more types of machinery in the database and assess their environmental impacts under the life cycle assessment (LCA) methodology.

5. Conclusion

This paper presented an alternative approach in emission accounting compared with what has been introduced by prior research. The study took a top-down approach and strived to use already existing data to perform a screening measure on tailpipe emissions. The operational emissions were quantified by the recent EEA/EMEP guidebook as well as documented data related to the operational performances of wheel loaders.

Instead of using rated power and annual hours of use, fuel consumption per effective hour was used as the main input to calculate in-use emissions. Along with the fuel consumption, utilization of effective hour as the measure of operational efficiency showed to be a prominent solution to the issue of annual operational hour. Such an approach helped to resolve uncertainties rooted in machine aging and quantify deterioration per effective hour, in lieu of operation hour and engine lifetime in calendar years.

The results show that although bigger engine size and higher fuel consumption (accompanied with longer economic lifetimes) results in having higher total in-use emissions, the load capacity of equipment can demonstrate a different picture of emissions. Meaning that as the efficiency of machinery in the unit of liter of fuel per cubic meter of moved volume got higher, the corresponding emissions showed lower values. Such a condition was recognized by comparing machine A with machine B and C.

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