Annex 50

A Report from the IEA Advanced Motor Fuels Technology Collaboration Programme

Fuel and Technology Alternatives in Non-Road Engines

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Summary/Abstract

The Swedish Transport Administration acted as operating agent for the Annex 50 project. This report was composed by Swedish Environmental Research Institute (IVL) in collaboration with partners in Sweden, Finland, Germany, Switzerland and Canada. The partners were governmental authorities, research institutes and universities, as well as private companies.

The objectives of Annex 50 were to analyze information about non-road mobile machinery and use measurement data to 1) evaluate the fuel efficiency and emission performance 2) develop emission factors 3) assess how retrofit influence fuel efficiency and emissions, 4) investigate strategies to reduce emissions, 5) present a description of national emission inventory models, 6) develop common test procedures, 7) compile information on non-road machinery policy options.

Mobile sources of air pollution can be divided into two categories: on-road sources and non-road sources. This report focus on agriculture tractors and construction equipment, and the term non-road engine will refer solely to engines used in non-road vehicles and equipment within these sectors. Non-road mobile machinery (NRMM) contributes significantly to overall emissions of green-house gases and air pollutants (18% of EU's CO2-emissions).

Engines sold today are required to meet PM and NOX emission limits that are approximately 95% lower than Tier 1/Stage I limits introduced in the mid-1990s. With the implementation of Tier 4i/Stage IIIB standards, in-cylinder controls were in general no longer sufficient to meet emissions

requirements and aftertreatment devices became common in non-road engine designs.

Current non-road regulatory programs lag behind on-road diesel engines, and are not stringent enough to compel the use of the best technologies for the control of PM and NOX: DPF and SCR systems. Use of particulate filters actually seems to have decreased with the transition from Tier 4i/Stage IIIB to Tier 4f/Stage IV in the EU. The implementation of proposed Stage V standards should lead to the universal application of DPFs for non-road engines 19-560 kW. Cost and the profitability for machine users will be the deciding factor in determining the success of a mainstream alternative for fuel and technologies. Providing the alternative fuels and the necessary powertrain concepts are not yet available for practical application, and many are still under various stages of development. The most important for future fuel potential are; raw material, energy efficiency, production technology, technical maturity or stage of development.

Rapeseed oil fuel and biodiesel were considered as best alternatives to diesel fuel in agriculture and forestry; least advantageous was electrical drive with hydrogen fuel cells. There is a limited demand for retrofitting of non-road machinery to ethanol. Ether-based substances such as DME or OME are not compatible with current fuel injection systems. Natural gas provides an interesting opportunity, as creation of the infrastructure offers potential to switch to biomethane in the future. Dual fuel has potential but is not yet fully mature, and a conversion to dual fuel (methane and diesel) is better suited for new machines than existing ones. Regarding hybridization there are few judgments about the different potential for different alternatives. The non-road emissions models used in Sweden, Germany and Finland are similar to each other and basically based on the same methodology. There is a significant need for more real-life emission measurement to improve the emission factors. Standardization of the models in different countries is also desirable.

The most influential policy instruments in order to influence non-road machinery have been identified as following: regulation of CO2 emissions, refund of energy tax on biofuels, fuels taxation (biofuels exempted), requirement of a renewable minimum share in fuel, demonstration projects for use of biofuels, enable type approvals tractor engines using biogas, retrofitting of machinery stock, introduction of Low Emission Zone (LEZ) and environmental requirements in municipal tenders (public procurement).

The main strategies for future policy instruments may be fuel taxation, estimation of fuel consumption and CO2 emissions in a standardized way, subsidies for retrofitting of old machines, replacement of old machinery with new, introduction of emission classes for electrified machinery and subsidies for purchasing new machinery powered by electricity.

Construction and industrial sectors are believed to be better suited for policies than other sectors due to the relative stationarity and the large proportion of work commissioned by the public sector.

Through the evaluation of measurement data from Sweden, Finland, Canada and Switzerland the key findings are;

- Machinery fleet proves a clear and consistent drop in NO_X-emissions in line with the emission standards.
- Still, the emission factors are in general slightly higher than the emission limits, though this conclusion is uncertain.
- Emission factors seem to be at similar level within the same emission standard, regardless of the engine power.

- Used test cycles and evaluation methods of the data have in general limited influence of the resulting emission factors, even though the variety is large.
- SCR has strong effect on NO_X-emission reduction and is mandatory for achieving the Stage IV NO_X-emission regulation in 56 kW to 560 kW category engines. EGR has more limited effect on NO_X-emissions.
- DPF is the most effective way to reduce particle emissions and will be necessary to comply with future regulations.
- DOC has a strong reduction effect on HC and CO emissions.
- Retrofitted (old) machinery seems to perform as good as new equipment, if similar aftertreatment technologies are used.
- The emission effects of using biofuels and diesel-water emulsion is not clear, except that biodiesel seems to reduce particle mass about 30% due to in general smaller and lighter particles.
- No clear conclusion was drawn from the analysis of machinery ageing.

A computer simulation is a powerful tool for studying the behavior of dynamic systems. The simulation approach proposed can be used to define the energy consumption during a working cycle. The energy efficiency of non-road machines can be improved especially in cases where high torque is needed at low speeds. In the case of a diesel-electric powertrain with no energy storage on-board, regeneration power can still be exploited. To be able to simulate the wheel loader energy consumption realistically, the work cycle has to be included. The model can be changed to predict interaction forces for some other material by adjusting model parameters.

The simulation was not optimized to evaluate a wholly electrified powertrain.

Authors

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Partners and sponsors

The Swedish Transport Administration acted as operating agent for Annex 50 project. Other partners in the project were:

- Canada, through Natural Resources Canada
- Finland, through the Technical Research Centre of Finland (VTT)
- Germany, through the Fachagentur Nachwachsende Rohstoffe (FNR)
- Switzerland, through the Swiss Federal Office of Energy (SFOE)

The institutes that carried out measurements or provided data were:

- Canada: Environment and Climate Change Canada
- Finland: VTT
- Sweden: AVL MTC
- Switzerland: Federal Department of Economic Affairs
- Germany: ifeu

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- Proventia Emission Control

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Table of Contents

Abbreviations

AMF – advanced Motor Fuels

ABT – averaging, banking and trading program

AH – air handling

ASC – ammonia slip catalyst

ATD – aftertreatment devices

BAT – best available technology

BC – black carbon

cEGR – cooled external EGR

CEPA – Canadian Environmental Protection Act

CI – compression ignition

CF – conformity factor

CLRTAP- Convention on Long-range Transboundary Air Pollution

CO – carbon monoxide

CO_2 – carbon dioxide

CPC - Condensing Particle Sizer

CR – high pressure common rail

DOC – diesel oxidation catalyst

DOES2 – Dynamic Dilution On/Off-road Exhaust Emissions Sampling System

DPF – diesel particulate filter

ECU – electronic control unit

EDI – electronic direct injection

EEA – European Environmental Agency

EEPS - Engine Exhaust Particle Sizer

EFM – exhaust flow meter

EGR – exhaust gas recirculation

EPA – Environmental Protection Agency

ERMS – Emissions Research and Measurement Section

EUI – electronic unit injection

FG – fixed geometry

FIE – fuel injection equipment

GHG – greenhouse gas

HC – hydrocarbons

HD – heavy duty

IDI – indirect injection

ICE – internal combustion engines

IEA – International Energy Agency

iEGR – internal EGR

IPCC – intergovernmental panel on climate change

KBA – German Federal Motor Transport Authority

LD – light duty

LPG – liquid petroleum gas

LSD – low sulfur diesel

MDI – mechanical direct injection

MY – model year

NA – naturally aspired

NMHC – non-methane hydrocarbons

NO_X – nitrogen oxides

NRMM – non-road mobile machinery

NRSC – non-road steady cycle

NRTC – non-road transient cycle

NTE – not-to-exceed

OBD – on-board diagnostic

OEM – original equipment manufacturers

$PM_{2.5}$ –particulate mass with diameter < 2.5 μm

PN – particle number

PTO – Power take off

SCR – selective catalytic reduction

SI – spark ignition

SMED – Svensk Miljöemissionsdata (Swedish Environmental Emission Data)

TC – turbocharged

THC – Total hydrocarbons

UBA – Umweltbundesamt

ULSD – ultra-low sulfur diesel

UNFCCC– United Nations Framework Convention on Climate Change

VGT – variable geometry turbocharger

Introduction

Mobile sources of air pollution can be divided into two categories: on-road sources and non-road sources. On-road sources include vehicles used in on-road applications, and primarily consist of light- and heavy-duty vehicles used for passenger and goods transport. Specialty on-road vehicles, such as refuse trucks and emergency response vehicles, are also included in this sector.

The non-road sector encompasses a very diverse and broad range of vehicle and equipment types. Major non-road engine applications include locomotives, aircraft, marine vessels, and equipment used in construction and agriculture industries. This report focus on agriculture tractors and construction equipment, and the term non-road engine will refer solely to engines used in non-road vehicles and equipment within these sectors, and will exclude other non-road sources such as locomotives, aircraft, and marine vessels.

Non-road mobile machinery (NRMM) contributes significantly to overall emissions of green-house gases and air pollutants. As an example, NRMM is the source of 18% of EU's CO_2 emissions (Swedish Transport Administration, 2012a). In spite of this, discussions regarding alternative fuels and GHG emissions are mainly focused on road vehicles, both within IEA AMF and in general.

This Annex adds unbiased knowledge for NRMM machinery as a complement to the already complied on-road data obtained in e.g. Annex 37 (Nylund and Koponen), Annex 43 (Laurikko) and Annex 49 (Nylund). AMF has also been reviewing fuel effects of NRMM emissions in other Annex for over ten years, e.g. Annex 25 - *Fuel Effects on Emissions from Non-Road Engines* (Murtonen and Nylund, 2003). During this period, technology and emission performance have changed substantially.

Objectives

The objectives of Annex 50 were to:

1. Test different types of machinery using both real-world measurements and measurements in laboratories and use data to:
    a. evaluate the fuel efficiency and emission performance of different engine technologies, fuel specifications and machinery applications including engine load cycles.
    b. develop emission factors for inventories of mobile non-road emissions in the participating countries.
    c. carry out an assessment of how retrofit of the legacy fleet would influence fuel efficiency and emissions
2. Investigate different possible strategies to reduce emissions from non-road machinery including potential spill-over effects from road vehicle technology.
3. Present a description of national emission inventory models used in the participating countries and compare modeled national emissions between the countries.
4. Develop common test procedures and protocols including measurement equipment, operating conditions and load cycles
5. Compile regional information on non-road machinery policy options

Vehicle emission regulations

Non-road emission regulations

Major end-use sectors for non-road engines are similar in the United States (US), Canada and the European Union (EU) and include agriculture, forestry, construction, mining, and commercial industries. Engine types used in non-road vehicles and equipment vary by power class and application, and the most common are:

- Compression-ignition (CI), diesel fueled (construction equipment, agriculture machinery, industry machinery)
- Spark-ignition (SI) engines, mainly gasoline fueled (garden equipment, recreational vehicles and crafts)

Regulatory pathways in the US and the EU have differed for non-road CI and SI engines, with standards for CI engines implemented prior to those for SI engines in both regions. This analysis focuses on non-road diesel engines and will touch only briefly on aspects of SI. A key distinguishing characteristic of the non-road engine market is the wide variation in the power rating, and engine power can span several orders of magnitude, from small (< 8/19 kW) engines to very large (> 560 kW) engines. Some applications, such as skid steer loaders or refrigeration units, utilize a relatively narrow range of power. In contrast, installed engine power can span several hundreds of kilowatts for equipment such as agricultural tractors or excavators.

In both US and EU regulatory programs, the stringency and timing of emission standards vary across engine power classes. ICCT divide NRMM (within the concerned sectors) into the following categories:

1. Agricultural tractors
2. Combine harvesters
3. Skid steer loaders
4. Tractors/loaders/backhoes
5. Wheel loaders
6. Crawler tractors/dozers
7. Excavators - small
8. Excavators - medium
9. Excavators - large
10. Non-road trucks
11. Generator sets
12. Pumps
13. Refrigeration units
14. Air/gas compressors
15. Lawn & garden equipment

In general the diversity of equipment types used in the agriculture sector is much lower than what is the case for the construction sector. Activity in agricultural applications is dominated by agricultural tractors (other types include combines, balers, and irrigation sets). The construction industry has a much broader range of equipment types, major types include loaders, excavators, non-road trucks and backhoes.

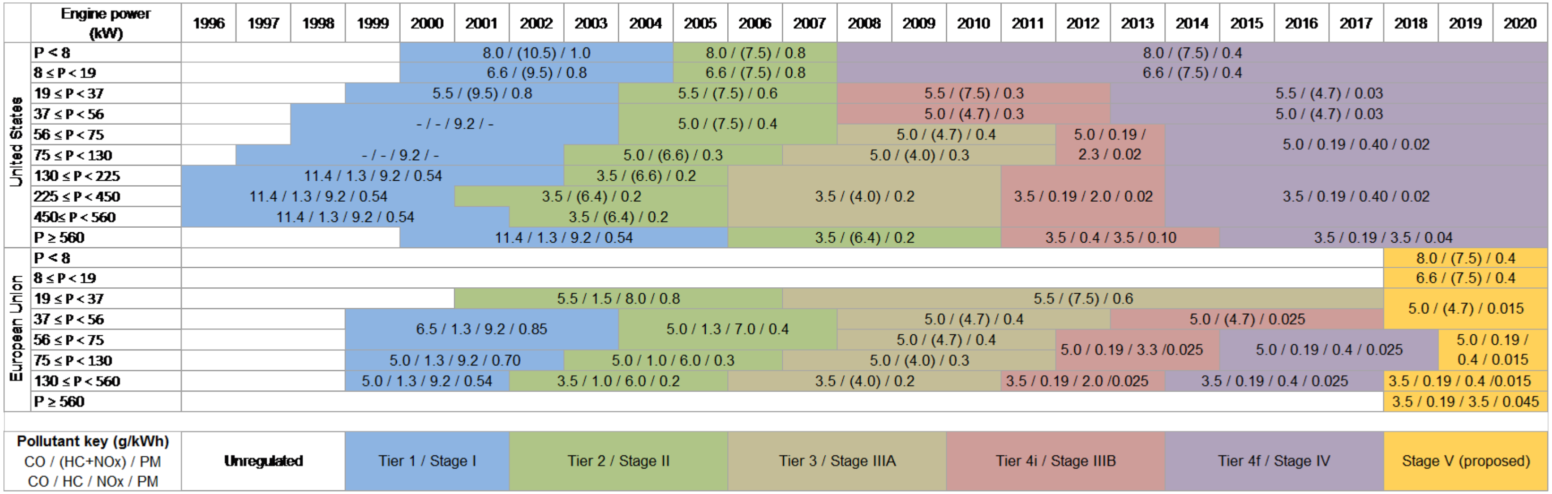
The diversity in non-road applications is relevant to the development of emission control technologies, as duty cycles and operating conditions can vary considerably for different types of non-road equipment.

The US Environmental Protection Agency (EPA) promulgated emission standards for non-road diesel engines for the first time in 1994, followed by the European Union in 1997. More stringent EPA emission standards are divided into Tiers, while EU emission standards progress in Stages. Regulated pollutants include

- Nitrogen oxides (NO_X)
- Particles (mass) (PM)
- Hydrocarbons (HC)
- Carbon monoxide (CO)

Legislation has periodically also been based on the parameter ($HC + NO_X$). The EPA also regulates *smoke* emissions from non-road diesel engines, while *ammonia slip* emissions have been regulated in the EU beginning with Stage IIIB standards. In the following sections there is a brief introduction to the most important emissions regulations concerning NRMM in the EU and US regions and some other countries.

Figure 1 shows an overview of emission standards in the US and EU, with both introduction years of Tiers and Stages as well as emission limits.



	Engine power (kW)	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
United States	P < 8					8.0 / (10.5) / 1.0					8.0 / (7.5) / 0.8			8.0 / (7.5) / 0.4												
	8 ≤ P < 19					6.6 / (9.5) / 0.8					6.6 / (7.5) / 0.8			6.6 / (7.5) / 0.4												
	19 ≤ P < 37				5.5 / (9.5) / 0.8					5.5 / (7.5) / 0.6				5.5 / (7.5) / 0.3					5.5 / (4.7) / 0.03							
	37 ≤ P < 56			- / - / 9.2 / -						5.0 / (7.5) / 0.4				5.0 / (4.7) / 0.3					5.0 / (4.7) / 0.03							
	56 ≤ P < 75													5.0 / (4.7) / 0.4				5.0 / 0.19 / 2.3 / 0.02		5.0 / 0.19 / 0.40 / 0.02						
	75 ≤ P < 130		- / - / 9.2 / -						5.0 / (6.6) / 0.3				5.0 / (4.0) / 0.3													
	130 ≤ P < 225	11.4 / 1.3 / 9.2 / 0.54							3.5 / (6.6) / 0.2			3.5 / (4.0) / 0.2					3.5 / 0.19 / 2.0 / 0.02			3.5 / 0.19 / 0.40 / 0.02						
	225 ≤ P < 450	11.4 / 1.3 / 9.2 / 0.54					3.5 / (6.4) / 0.2																			
	450≤ P < 560	11.4 / 1.3 / 9.2 / 0.54						3.5 / (6.4) / 0.2																		
	P ≥ 560					11.4 / 1.3 / 9.2 / 0.54						3.5 / (6.4) / 0.2					3.5 / 0.4 / 3.5 / 0.10				3.5 / 0.19 / 3.5 / 0.04					
European Union	P < 8																							8.0 / (7.5) / 0.4		
	8 ≤ P < 19																							6.6 / (7.5) / 0.4		
	19 ≤ P < 37						5.5 / 1.5 / 8.0 / 0.8						5.5 / (7.5) / 0.6											5.0 / (4.7) / 0.015		
	37 ≤ P < 56				6.5 / 1.3 / 9.2 / 0.85					5.0 / 1.3 / 7.0 / 0.4				5.0 / (4.7) / 0.4					5.0 / (4.7) / 0.025							
	56 ≤ P < 75													5.0 / (4.7) / 0.4				5.0 / 0.19 / 3.3 /0.025			5.0 / 0.19 / 0.4 / 0.025				5.0 / 0.19 / 0.4 / 0.015	
	75 ≤ P < 130				5.0 / 1.3 / 9.2 / 0.70				5.0 / 1.0 / 6.0 / 0.3				5.0 / (4.0) / 0.3													
	130 ≤ P < 560				5.0 / 1.3 / 9.2 / 0.54			3.5 / 1.0 / 6.0 / 0.2				3.5 / (4.0) / 0.2					3.5 / 0.19 / 2.0 /0.025			3.5 / 0.19 / 0.4 / 0.025				3.5 / 0.19 / 0.4 /0.015		
	P ≥ 560																							3.5 / 0.19 / 3.5 / 0.045		

Pollutant key (g/kWh) CO / (HC+NOx) / PM CO / HC / NOx / PM	**Unregulated**	Tier 1 / Stage I	Tier 2 / Stage II	Tier 3 / Stage IIIA	Tier 4i / Stage IIIB	Tier 4f / Stage IV	Stage V (proposed)

Figure 1. Emission standards for non-road diesel engines in the United States and the European Union. Adapted from ICCT (2016).

United States (US)

Tier 1

Tier 1 regulations for engines with installed power ≥ 37 kW were first promulgated in 1994 and phased in between 1996 and 1998 depending on engine power class. Tier 1 standards were first introduced for engines with power class 130 - 560 kW due to their similarity to on-road engines, followed by engines with a power range of 75-130 kW in 1997 and 37-75 kW in 1998. Tier 1 for engines < 37 kW was introduced in 1999. Tier 1 emission standards aimed primarily to reduce NO_X and smoke emissions. HC, CO, and PM standards were included for engines ≥ 130 kW in order to provide regulatory harmonization with California and the EU.

Tier 2

Tier 2 standards were implemented between 2001and - 2006 depending on engine power class and generally parallel to 1998 on-road heavy-duty (HD) vehicle standards. Emission limits for PM were reduced by 63% for 130–560 kW engines and were included for the first time for 37–130 kW engines. Tier 2 introduced a combined limit for non-methane hydrocarbons (NMHC) and NO_X. Crankcase emissions from naturally aspirated engines were regulated for the first time. Tier 2 inclusion of durability requirements increased the stringency, and that performance was maintained throughout the useful life of an engine.

Tier 3

Tier 3 was phased in between 2006 and- 2008 for engines 37 - 560 kW and parallel to 2004 on-road HD vehicle standards. The NMHC + NO_X limit was reduced by 37–39% for power class 37 - 560 kW. Tier 3 standards were not set for very large (> 560 kW) engines or very small engines (< 19 kW).

Tier 4

Tier 4 was adopted in 2004 and implemented between 2008 and 2014. Tier 4 standards treat engines and fuel as a system in the sense that the diesel fuel sulfur content was reduced by 99% (influences emissions of SO_2 and PM). A new non-road transient cycle (NRTC) was introduced, along with not-to-exceed (NTE) requirements. NRTC and NTE tests were required from 2011 for 130 – 560 kW engines, from 2012 for 56 – 130 kW engines, and from 2013 for engines < 56 kW. Engines > 560 kW and constant speed, variable-load engines were exempted from testing on the NRTC.

Tier 4 interim (4i) standards were set for 19 – 56 kW engines in 2008 and for > 560 kW in 2011. For the 56 – 130 kW and 130–560 kW power ranges, manufacturers could either choose for alternate standards or a percentage phase-in of Tier 4 engines (NO_X). The Tier 4 final (4f) standards for 56 – 560 kW engines were expected to compel the widespread use of aftertreatment technologies for PM and NO_X control. For engines ≤ 19 kW the standards were less stringent than for engines > 19 kW.

Separate standards were set for generator sets with power > 560 kW as well as for engines with power > 900 kW. Relative to the EPA 2010 standards for on-road HD diesel engines, notable omissions from the Tier 4 rulemaking include on-board diagnostic (OBD) requirements and mandatory in-use compliance testing provisions.

Canada

In Canada NRMM emissions are regulated under the Canadian Environmental Protection Act 1999 (CEPA 1999). The non-road Compression-Ignition Engine Emission Regulations (SOR/2005-32) were published in 2005. These regulations introduced emission standards for new compression-ignition engines of the 2006 and later model years used for non-road mobile applications in construction, mining, farming-, and forestry equipment such as backhoes, tractors, excavators, and log skidders.

The Canadian emission standards aligned with the US Environmental Protection Agency (EPA) rules for non-road diesel engines and in 2012 Canadian regulations were amended to include more stringent Tier 4 standards. Engine emission standards are regulated for NMHC + NO_X, CO and PM. Compliance with emissions standards is demonstrated under prescribed emissions testing procedures, using an engine dynamometer (ERMS, 2017).

The Regulations apply to manufacturers and importers of new compression-ignition engines, who operate in Canada, and whose engines are for the purpose of sale. Emissions for other categories of NRMM are regulated under the *Marine Spark-Ignition Engine, Vessel and Off-Road Recreational Vehicle Emission Regulations* (SOR/2011-10) and the *Off-Road Small Spark-Ignition Engine Emission Regulations* (SOR/2003-355).

European Union (EU)

Stage I

Stage I emission standards were laid out in Directive 97/68/EC promulgated by the European Commission and phased in from 1999 to 2002, and for agricultural tractors in a separate directive adopted in 2000. Stage I limits applied to power ratings 37- 560 kW, and emission parameters included HC, CO, and PM.

Stage II

Stage II standards were phased in between 2002 and- 2003 for 18-560 kW engines. Emission standards for PM and NO_X were reduced by 50–60%.

Stage IIIA

Stage IIIA (and Stage IIIB) standards were promulgated in 2004 through Directive 2004/26/EC and phased in between 2006 -and 2007. Constant-speed engines were included for the first time. Stage IIIA standards introduced a flexibility program for engine manufacturers, which allows for the market placement of a limited number of engines certified to the previous Stage of emission limits during the period between two successive regulatory Stages. The flexibility program is applicable for all transitions from Stage II through Stage IV.

Stage IIIB

Stage IIIB standards regulate engines between 37- and 560 kW, and its PM standards for 37–56 kW are 92% lower than the corresponding Tier 4i limits. Constant speed engines were exempted from the regulations, as were engines <37 kW. Stage IIIB enforced a limit on emissions of ammonia slip, which were <25 ppm (NTE). Transient testing on the NRTC was required for all regulated power class beginning with Stage IIIB.

Stage IV

Stage IV standards for non-road engines and for agricultural and forestry tractors were adopted in 2005 through Directive 2004/26/EC. Stage IV standards were implemented in 2014 and largely mirror EPA Tier 4f standards for most power classes, except 19- 37 kW engines (Stage IIIA level continued). Stage IV standards tighten the ammonia emission limit to 10 ppm.

Stage V

The Stage V standards are effective from 2019 for engines < 56 kW and > 130 kW, and from 2020 for engines of 56-130 kW. Stage V will introduce particle number (PN) limits, as well as engines <19 kW and >560 kW for the first time. Stage V standards also include manufacturer-run in-use compliance programs, but only entail monitoring and reporting requirements.

Other countries

Many countries around the world have adopted regulations for non-road engines equivalent to US or EU programs. Japan and South Korea have already implemented Tier 4f equivalent standards. China non-road standards are currently equivalent to Stage IIIA and adopted standards equivalent to Stage IIIB and IV, though implementation dates have yet to be announced. India has adopted US Tier 3 standards. (ICCT, 2016)

Comparison On-road versus Non-road emission regulations

On-road HD diesel engines were subject to regulation prior to non-road engines in the US and the EU. Regulatory programs developed for on-road diesel engines thus provided a model for subsequent programs implemented to control emissions from non-road diesel engines. In general, emission standards for non-road diesel engines have lagged behind similar on-road engine standards by about 2-6 years, but this gap has been reduced with more recent non-road regulatory Tiers/Stages.

The progression of emission standards (CO, NO_X, HC, HC+NO_X, PM) for on-road HD diesel engines and NRMM in the two regions (US and EU) are illustrated in Figure 2-6. The two non-road diesel engine classes that are most similar in size to on-road engines, are 75–130 kW and 130–560 kW. The diagrams show the emission limit in g pollutant per engine work output (g/kWh).

Legend:

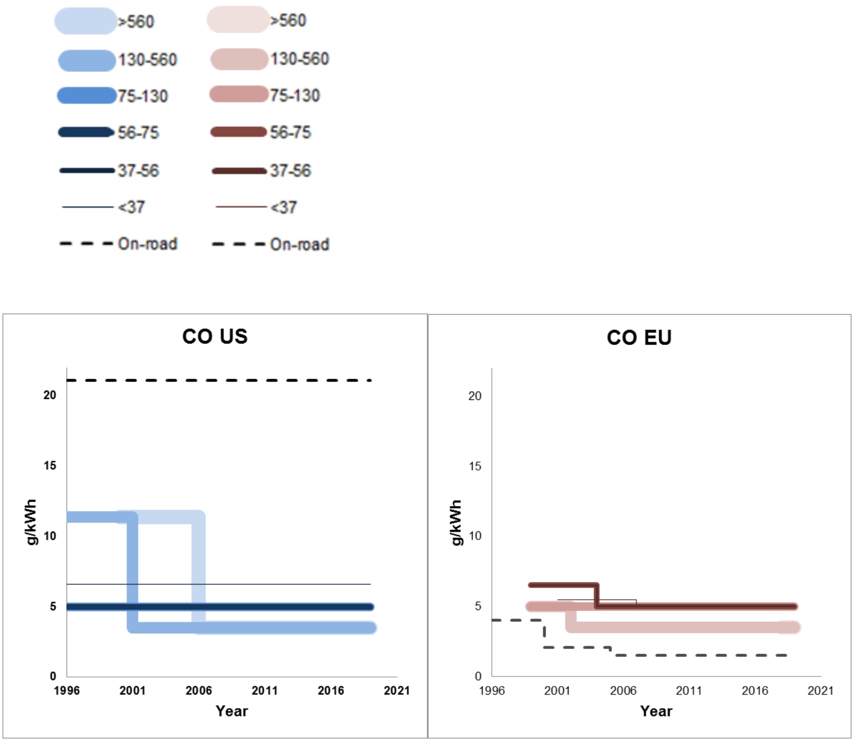


Figure 2. Progression of CO emission standards for on-road HD diesel engines and non- road mobile machinery in the two regions (US and EU).

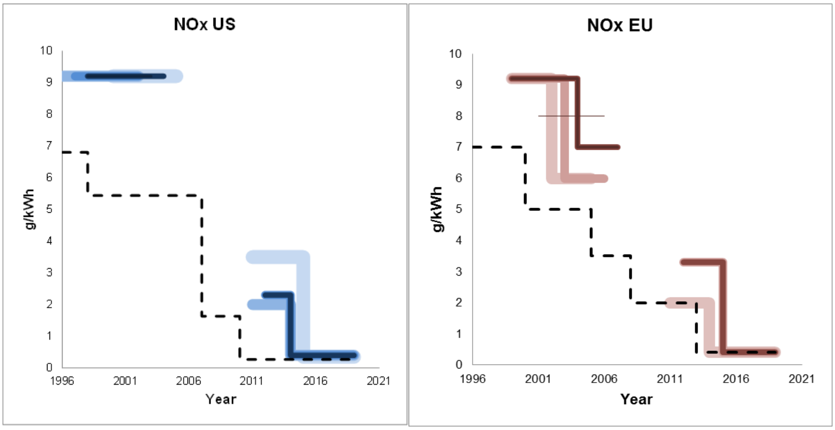


Figure 3. Progression of NOx emission standards for on-road HD diesel engines and non- road mobile machinery in the two regions (US and EU).

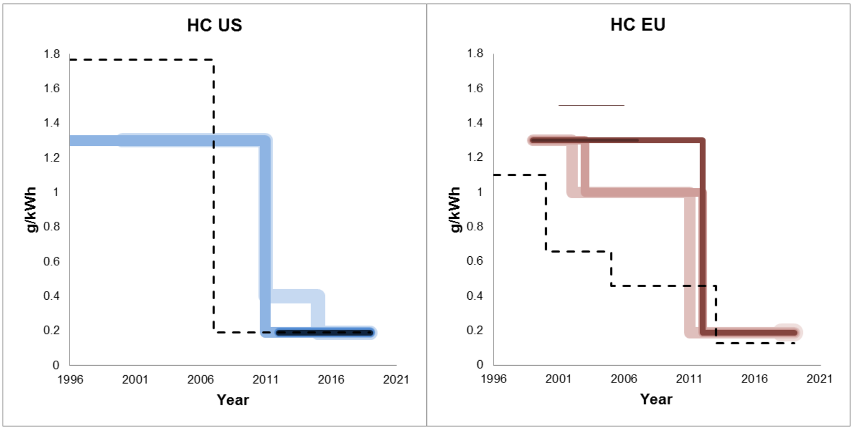


Figure 4. Progression of HC emission standards for on-road HD diesel engines and non-road mobile machinery in the two regions (US and EU).

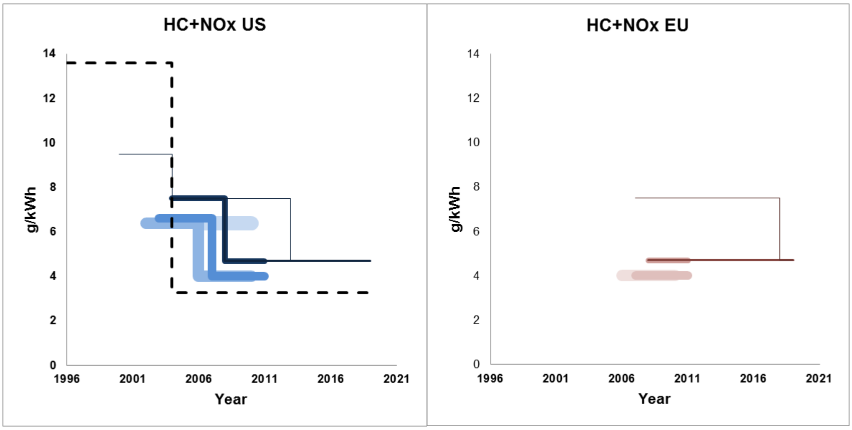


Figure 5. Progression of HC+NOx emission standards for on-road HD diesel engines and non-road mobile machinery in the two regions (US and EU).

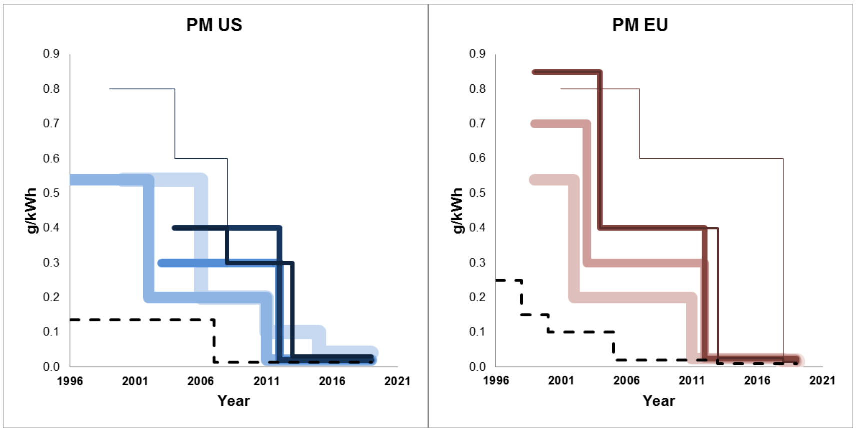


Figure 6. Progression of PM emission standards for on-road HD diesel engines and non-road mobile machinery in the two regions (US and EU).

Emission control technology pathways

Emission control strategies

The complexity of the non-road engine market, which is characterized by a much wider range of power classes and applications than the on-road sector, has led to a greater degree of variability in emission control strategies. Non-road engine manufacturers face a number of additional design challenges unique to their equipment market. Advanced diesel engine emission control strategies and technologies were first developed for on-road engines, and many technologies later adopted in non-road engine designs (Stage I - Stage IIIA). For Stage IIIB - Stage IV the development has rather been parallel. To meet standards, similar technologies are utilized in the EU and the U.S.

A variety of technologies and strategies have been developed to control air pollutant emissions from diesel engines. Broadly, these emission control strategies can be subdivided into two groups:

- in-cylinder approaches
- exhaust aftertreatment devices

In-cylinder approaches encompass engine design changes that aim to limit pollutant formation, and emission control is achieved primarily through developments and modifications of the fuel injection and air handling systems. For in-cylinder emission control approaches, there is often a trade-off between control of PM and control of NO_X.

The adoption of increasingly stringent regulatory programs has lowered emission standards to a point where in-cylinder strategies are not sufficient to control both NO_X and PM emissions. Succeeding regulatory Stages introduced more stringent requirements and led to the development and widespread use of aftertreatment control technologies.

The key aftertreatment technologies applied in the non-road sector include diesel particulate filters (DPF) for the control of PM and selective catalytic reduction (SCR) systems for the control of NO_X. For aftertreatment technologies, fuel quality is important and especially the sulfur content can affect both the performance and durability of aftertreatment systems. Table 1 provides a brief overview of technologies used for emission control, divided into in-cylinder and after treatment technologies:

Table 1. Overview of emission control technologies used in non-road mobile machinery (adapted from ICCT, 2016).

	Name Technology	**Short name**	**Pollutants targeted**	**Description**
In-cylinder technologies	Fuel injection	FIE	PM, NO_X, HC, CO	Increased injection pressure promotes fuel atomization and better air and fuel mixing, resulting in improved combustion efficiency.
	Rate of fuel injection, multiple injections	FIE	NO_X	Fine tuning of fuel injection by varying rate of injection or using multiple injections. Multiple injection strategies require electronically controlled high-pressure unit injectors or common rail injection systems.
	Fuel injection timing advanced	FIE	PM, CO, HC	Advanced or delayed fuel injection to tune combustion process. Advanced timing increases combustion pressures and temperatures resulting in improved fuel efficiency. Delayed fuel injection timing reduces NO_X emissions at the expense of
	Fuel injection timing delayed	FIE	NO_X	

				fuel economy and PM emission penalties.
	Turbocharger	TC	PM, CO, HC	Compressor used to boost intake air pressure. Wastegated, multiple-stage, and variable geometry turbochargers developed to improve turbocharger performance over a broad range of engine operating conditions.
	Charge air cooling		NO_X	Heat exchanger used to lower temperature of gases entering combustion chamber to reduce peak combustion temperatures.
	Exhaust gas circulation	EGR	NO_X	Portion of exhaust gas mixed with intake air to serve as diluent and reduce peak combustion temperatures. In internal EGR (iEGR) residual exhaust is retained within the combustion chamber, and external high pressure loop systems where exhaust gas is routed from upstream of the turbocharger exhaust turbine to the intake manifold. Cooled EGR (cEGR) systems incorporate a cooler to increase system NO_X reduction efficiencies.
Aftertreatment devices	Diesel oxidation catalyst	DOC	PM, HC, CO	Flow-through catalytic converter composed of a monolith honeycomb substrate coated with a platinum group metal catalyst.
	Diesel particulate filter	DPF	PM (organic soluble)	Wall-flow filtration device. Filters are regenerated using active and/or passive regeneration methods to oxidize and remove collected particles.
	Selective catalytic reduction	SCR	NO_X	Catalytic reduction of NO and NO_2 to N_2 and H_2O using ammonia as reducing agent. Catalysts types include vanadium, iron-exchanged zeolite, and copper-exchanged zeolite. Catalysts vary in effective temperature ranges, exhaust NO2/ NO_X sensitivity, and sulfur tolerance. Ammonia is generated from the decomposition of a urea solution, which is referred to as diesel exhaust fluid in the United States and by the brand name AdBlue in Europe.
	Ammonia slip catalyst	ASC	NH_3	Oxidation catalyst used for the control of ammonia passing through the SCR system.

Design challenges for non-road engines

For **on-road** HD diesel engines, in-cylinder control strategies were often sufficient to meet requirements of the EPA 1998 and Euro IIIA regulations. EPA 2010 and Euro VI emission requirements also incorporate similar design elements: high-pressure variable fuel injection, cooled EGR, and an aftertreatment system of DOC, DPF, SCR, and ASC in series. However, **non-road** engine manufacturers face a number of design challenges unique to their equipment market compared to on-road, some are:

- **Cost**. Especially for smaller-sized engines, the cost of advanced emission control technologies relative to the cost of the engine can be prohibitive. For large power classes, costs associated with engine development must be recovered on a relatively low sales volume.
- **Packaging constraints.** Non-road engines must fit in a variety of equipment envelopes. Power class and shape changes resulting from the adoption of emission control technologies can affect sales and suitability of engines for specific equipment types.
- **Operating environment.** Non-road equipment is often used in more challenging environments than those encountered by on-road vehicles, leading to higher vibration and mechanical stress and increased exposure to dust. Also, the velocity of non-road equipment cannot be relied upon to cool the engine, resulting in thermal management challenges.
- **Duty cycles.** Engine operating modes tend to be different from on-road duty cycles. Key parameters for effective emission control design may differ (such as exhaust temperature), and work cycles over which control equipment must be effective, vary considerably.

Control strategies

This section considers the development and pathways of key technologies and engine modifications incorporated into non-road engine designs. On-road diesel engine technology developments provide a starting point for this assessment. A number of engine design parameters are identified to track non-road engine technology development over time. These include:

- fuel system type
- method of aspiration (e.g., naturally aspirated, turbocharger)
- engine modifications for emission control (e.g., variable injection timing)
- electronic engine controls
- exhaust gas recirculation
- use of aftertreatment devices

Further information specific to non-road diesel engines was obtained from the EPA's engine certification database, which compiles engine data submitted by engine manufacturers to the EPA during the certificate of the conformity application process. The EU does not compile similar data as US. However, due to the high degree of harmonization and the international nature of the market, general engine technology pathways are expected to be similar within corresponding regulatory Tiers/Stages. In the following sections there is a brief introduction to the most important control strategies for each regulatory step.

Control design by Tier or Stage

Tier 1 / Stage I

NO_X emission reductions were achievable through in-cylinder control strategies, including delayed fuel injection timing and turbochargers incorporating (air-to-air) charge air coolers. Smoke puff limiters or wastegates were also incorporated into Tier 1. Indirect injection, naturally aspirated engines were preferred for small engines (< 37 kW). Engine design characteristics for 75 - 560 kW are similar, and include mechanical direct injection and turbocharging.

Tier 2 / Stage II

Tier 2/Stage II includes the continued improvement of fuel injection systems, widespread adoption of electronic engine controls in larger power classes, and increased use of air-to-air charge air cooling systems with turbocharged engines. Advanced fuel injection technologies developed for on-road engines were transferred to non-road engine designs during this time period, enabling higher injection pressures.

For > 75 kW, rotary fuel pumps, electronic unit injectors and electronic engine controls were increasingly used to provide higher injection pressures and improved control over the process. Also, common rail systems were incorporated for the first time. Electronic controls were common in very large (> 560 kW) Tier 2 engines, and provides greater control over the combustion process and enable rate shaping and multiple injections. Turbochargers were incorporated into a greater percentage of 37–75 kW engines. Nearly all certified engines 75–560 kW incorporated fixed geometry or wastegated turbochargers with air-to-air charge air coolers.

Tier 3 / Stage IIIA

Tier 3/Stage IIIA emission standards were the final level for which in-cylinder controls were sufficient to meet requirements. For larger engines, external cooled EGR (cEGR) systems were common, while smaller power class incorporated external, cooled, or internal EGR (iEGR) systems. Advanced technology packages are more common for larger engines (130–560 kW), and full authority electronic engine controls are also common in this size range.

For smaller power classes (35-75 kW), many engines continued to utilize mechanical fuel injection, with improvements (rotary pump or unit pump fuel systems). In the 56–75 kW power class, common rail and electronic unit pump fuel systems are used more frequently. Most of the smaller engines are equipped with either fixed geometry or wastegated turbochargers, and sometimes charge air cooling systems.

Tier 4i / Stage IIIB

Two engine design pathways emerged for 56–560 kW engines at this Tier/Stage: tune engines for low engine-out PM emissions and control relatively high NO_X emissions with SCR; or of PM aftertreatment devices such as DPF and/or DOC along with cEGR for NO_X control.

SCR-only engines were developed for use in mobile and crawler cranes, which are characterized by intermittent, low-load duty cycles.

Additional technologies are common rail fuel injection systems, multi-stage turbochargers, full authority electronic controls, and advanced engine calibrations. Power class 56 - 130 kW faced less stringent NO_X emission standards, after treatment technology packages primarily consist of cEGR + DOC + DPF or SCR only. Tier 4i emission standards for engines >560 kW were mostly met without the need for aftertreatment control technologies, however some use DOCs, cEGR or SCR.

Tier 4f / Stage IV

There is a widespread adoption of SCR for engines between 56 - 560 kW due to the stringent NO_X requirements. cEGR is used along with SCR in some engine designs.

DPFs are particularly included in some larger engines (agricultural tractors). Engines 56 - 560 kW without DPFs emits approximately 4 - 5 times as much PM as comparably sized DPF-equipped engines.

Emission standards for engines 19 - 37 kW remain at Stage IIIA and can be met without the need for advanced after treatment technologies. Indirect injection engines remain common in the < 19 kW power class with the implementation of Tier 4f. For large engines (> 560 kW), Tier 4f generally includes both cEGR and DOC or SCR, and electronically controlled, high-pressure direct fuel in injection systems and turbocharging with charge air cooling.

Tier 4i/Stage IIIB and Tier 4f/Stage IV emission control technology packages for major non-road engine manufacturers can be found in the Appendix 1.

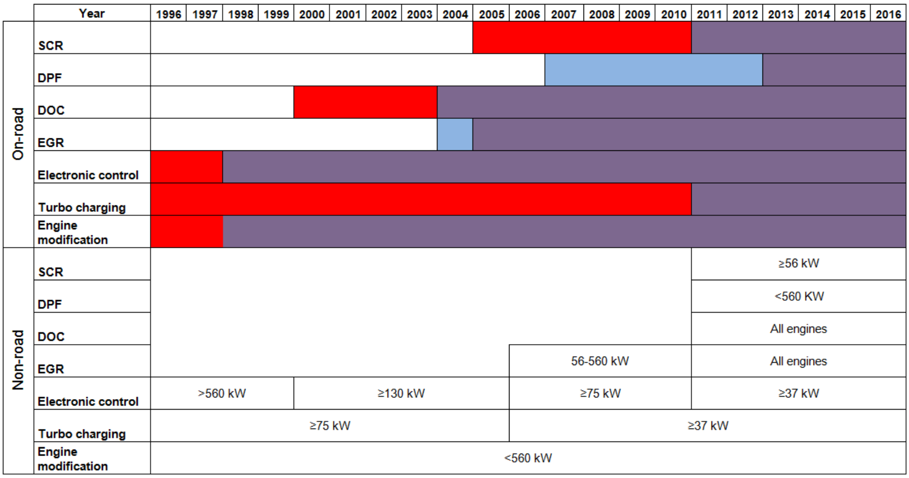
Stage V

The key technology response to the Stage V program will likely be near universal application of particulate filters and will be necessary to meet PM and PN limits for engines 19 - 560 kW. For engines 56 - 560 kW, emission control systems are expected to converge on a common design incorporating DOC, DPF, and SCR. For engines >560 and <19 kW technology packages are expected to follow those developed in response to the Tier 4f program.

Comparison of non-road and on-road control technologies

The development that has enabled emission reductions has largely been predicated on the transfer and integration of engine and emission control technologies developed for on-road engines into non-road engine designs. Non-road power classes with on-road analogues (~75-560 kW) were subjected to more stringent emission standards at an earlier date than power classes with no direct on-road counterpart.

Figure 7 shows a comparison of EPA and EU **on-road** control technology pathways for HD diesel vehicles (US- blue, EU- red, both- purple), and **non-road** control technology pathways (denoted by power interval).



	Year	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
On-road	SCR										🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟪	🟪	🟪	🟪	🟪
	DPF												🟦	🟦	🟦	🟦	🟦	🟦	🟪	🟪	🟪	🟪
	DOC					🟥	🟥	🟥	🟥	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪
	EGR									🟦	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪
	Electronic control	🟥	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪
	Turbo charging	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟪	🟪	🟪	🟪	🟪
	Engine modification	🟥	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪
Non-road	SCR																≥56 kW					
	DPF																<560 KW					
	DOC																All engines					
	EGR											56-560 kW					All engines					
	Electronic control	>560 kW				≥130 kW						≥75 kW					≥37 kW					
	Turbo charging	≥75 kW										≥37 kW										
	Engine modification	<560 kW																				

Figure 7. Degree of technology application for on-road engines and non-road engines by year. On-road degree of application is shown by color (blue US, red EU, purple both regions) and non-road is shown by engine power (engine power ranges in kW written in figures).

Conclusion

Engines sold today are required to meet PM and NO_X emission limits that are approximately 95% lower than Tier 1/Stage I limits introduced in the mid-1990s.

With the implementation of Tier 4i/Stage IIIB standards, in-cylinder controls were in general no longer sufficient to meet emission requirements and aftertreatment devices became common in non-road engine designs.

Emission control technology pathways for on-road HD diesel engines have largely converged and incorporated cEGR, DOC, DPF, and SCR. Larger engines have generally adopted SCR for NO_X control and DOC for PM control. For smaller engines, cEGR and oxidation catalysts are generally sufficient.

However, current non-road regulatory programs lag behind comparable programs for on-road diesel engines, and are not stringent enough to compel the use of the best available technologies for the control of PM and NO_X emissions from diesel engines: DPF and SCR systems. This is especially true for particulate filters, the use of which seems to actually have decreased with the transition from Tier 4i/Stage IIIB to Tier 4f/Stage IV in the EU. The implementation of proposed Stage V standards should lead to the universal application of DPFs for engines 19-560 kW.

Availability and applicability of non-road alternative fuels and technologies

Alternative liquid or gaseous fuels

General evaluation

Future options for diesel fuel alternatives have emerged. Cost and the profitability for machine users will be the deciding factor in determining the success of a mainstream alternative. It is necessary to take into consideration high load factors, fuel logistics, on-site fueling and high power density, combined with large machine variety and low market numbers (Bergmann, 2015).

Biofuels are subject to different international and national regulations which, in part, involve more requirements than those for fossil diesel fuels. For example, on EU level there are the Renewable Energy Directive (2009/28/EG) and the Fuel Quality Directive (2009/30/EG). The process chains for providing the alternative fuels and the necessary powertrain concepts remain, however, in part not yet available for practical application. Also, many are still under various stages of development (Remmele et al., 2014).

Alternative liquid and gaseous fuels for internal combustion engines (ICE) include:

- Fatty acid methyl ester (FAME) - “biodiesel”
- Straight vegetable oils, e.g. rapeseed oil

- Hydrogenated vegetable oils, “HVO”
- Ethanol-based fuel
- Methane (fossil or renewable)
- Dimethyl ether

These alternative fuels were discussed and evaluated in a technical discussion with several experts from industry, associations and scientific institutions at a conference initiated by the Association for Technology and Structures in Agriculture (KTBL) and the Technology and Support Centre (TFZ) (Remmele et al., 2014).

According to Remmele et al. (2014), the potential of the raw material and availability of the fuel, the energy efficiency and the production technology, as well as the technical maturity or stage of research and development, were all identified as the most important evaluation criteria.

The raw material potential and availability of the fuel were assessed to be the best for biodiesel. Also the technology of biodiesel production, as well as the fuel’s technical maturity and stage of research and development, were seen as the most advanced. With regard to nearly all the criteria, rapeseed oil fuel was rated throughout as advantageous to very advantageous. Rapeseed oil fuel and biodiesel were evaluated as best alternatives to diesel fuel in agriculture and forestry.

Assessed as least advantageous, marked down by high costs, poor technical maturity and through missing infrastructure, was electrical drive with hydrogen fuel cells.

Liquid biofuels

Liquid biofuels that are relevant for the options for diesel fuel alternatives are basically:

- Ester-based (FAME)
- Paraffinic (HVO, GTL)
- Ethanol-based (E85, ED95)

Ester-based fuels result in low soot emissions, but due to the introduction of Stage V this will have little relevance in the future. Additionally, the fuels are produced using food resources and contain catalyst poisoning substances, thus leading to higher NO_X emissions according to Bergmann (2015).

Second generation diesel alternatives like paraffinic fuels are closer to diesel, such as hydro-treated vegetable oil (HVO) or gas to liquid (GTL) also have little technical impact on current diesel engine systems, the usability of the existing fuel logistics and fueling procedures.

A study by the Swedish Board of Agricultures (2011) concluded that there is a limited demand for retrofitting of non-road machinery to ethanol. The main reason is the lack of technology for non-road engines for use with ethanol fuels.

Gaseous fuels

General

Ether-based substances such as dimethyl ether (DME) or oxymethylen ether (OME) have oxygen within their chemical structure which supports low soot formation. However, these fuels are not compatible with current fuel injection systems although they are liquid when pressurized (Bergmann, 2015).

Natural gas (NG) provides an interesting opportunity, as creation of the infrastructure offers potential to switch to biomethane in the future.
When NG is in its compressed form (CNG) it is more than five times lower in energy density when compared to diesel. It would also be challenging to refuel on site, and this becomes even more complex when in liquid form (LNG), which has an energy density two to three times lower than diesel. This does not exclude its use, especially in those sectors that can produce their own biomethane, the biological equivalent to natural gas, from by-products and waste. Biomethane could be considered a positive alternative when looking towards a more sustainable agricultural sector. (Bergmann, 2015).

Johannesson and Göthe (2011) judge that NRMM that can use existing infrastructure for gas is better suited for gas engines, whereas the cost of new infrastructure for gas supply has to be added to the development cost for new machinery that cannot use existing infrastructure.

The MEKA-project

A report by the Swedish Board of Agricultures (2014) describes and evaluates how three machines (agriculture tractors) were converted to dual fuel operation, running on gas and diesel within the framework of the Swedish “MEKA Project” government commission.

A conversion to dual fuel (methane and diesel) operation is better suited for entirely new machines than existing ones. This is due to the fact that conversion requires extensive adaptation of the engine. No retrofit companies have considered it possible to implement retrofits within the project. Therefore there is no evaluation of any alternatives which involve a retrofit of existing machinery.

Operational tests have shown that the dual fuel tractors have performed well. The total fuel consumption is higher for dual fuel operation than it is for pure diesel operation. This does affect fuel costs, however, the fuel prices have a bigger impact in total. Cost calculations point towards a saving in fuel costs of an average of four percent.

For the first generation of these dual fuel tractors, methane emissions account for 15-30 percent of their total climate impact. For the newest tractor model, the climate impact of dual fuel operation with biogas is approximately 40 percent lower than that of pure diesel operation.

The test results lead to the conclusion that the technology has potential, but is not yet fully mature. Further investigations are required to gain a better understanding of emissions of NO_X, PM and HC, and to observe the ageing of methane catalysts. Until there are regulations in place regarding dual fuel technology at an EU level, the current system of national exemptions is adequate to allow for the development and use of the technology.

Hybridization

General

Hybridization of NRMM is the partial electrification of either one or more of the machinery's propulsion and operational functions. If some of the energy is supplied by cable, the vehicle is considered to be a "plug-in hybrid" and if there is no external electrical power supply (and therefore the electrical parts of the drive train is only used for making the drivetrain more efficient), the vehicle counts as a "hybrid" (Larsson, 2012).

Since mobile machines often have several actuators[1] there are many possible combinations in which one or more of the components may be powered by electricity, while the rest is powered conventionally.

Engine and powertrain hybridization

Engine hybridization

When used together with an internal combustion engine, the electrical motor can be used in a serial or parallel configuration. Electric motors have a number of advantages over ICEs, in particular a high efficiency and high torque at low speeds. Electric motors can be powered by DC or AC, the

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[1] Actuators = A component of a machine that is responsible for moving or controlling a mechanism or system.

latter can be divided into induction, synchronous, and asynchronous motors. As for systems published in scientific journals, asynchronous and permanent magnet motors dominate, DC motors are slightly less explored and reluctance motors have a limited reach. Their strengths and weaknesses can be evaluated in terms of power density, efficiency, controllability, reliability, maturity and cost (Larsson, 2012).

It may be possible to increase the efficiency of the powertrain by adding an electric motor in series after the diesel engine in a diesel electric powertrain. By combining the internal combustion engine with an electric motor, it is possible to limit the use of the internal combustion engine to a few combinations of torque and speed, where the efficiency is high and emissions are low (Larsson, 2012).

Larsson further describes that if the electric motor is placed in parallel with the internal combustion engine, it can supplement the internal combustion engine, thus allowing a smaller engine to be used. Internal combustion engines tend to be most effective at high pressure and hence it is advantageous if they are as small as possible since they then more often will work at higher pressures.

By shutting down a combustion engine when not needed, and instead use the electric motor for the initial phase, fuel consumption decreases without decreasing vehicle performance. Diesel needs (electrical) starter motors when the fuel mixture must be compressed to ignite. The starter motor in a hybrid electric vehicle is however much larger than a regular starter.

Transmission hybridization

During an operating cycle, speed and power consumption vary extensively. This put requirements on the transmission to transform engine speed and torque to desired output speed with minimal loss. The engine power is used by multiple actuators that have different needs regarding e.g. speed and torque. Three types of transmissions occur in vehicles: mechanical, hydraulic and electric. Within the foreseeable future, it is primarily mechanical transmission that may be replaced by electrical transmission. Using an electrical transmission is desirable for several reasons:

- Ability to provide several devices with enough power.
- Increased flexibility as it is easier to handle cables than e.g. cylinders or chains.
- Increased controllability, which makes it possible to reduce losses from parasitic losses from auxiliary equipment.

Electrical systems (which allow other components, such as motors, to be used optimally) have lower transmission losses than mechanical and hydraulic systems. An internal combustion engine cannot use kinetic energy, which is possible with an electric motor which can also function as alternator.

Energy storage and supply

In a hybrid vehicle, energy can either be generated during operations or be supplied from an external source. In both cases, intermediate storage of energy is needed. With a hybrid machine, it is possible to have energy flows in both directions between the energy storage and energy use. The main alternatives to store energy in the hybrid machines are super capacitors and batteries. Other options include flywheels and hydraulic accumulators (Larsson, 2012).

Supercapacitors can be made of a number of materials where factors such as cost and need for high power or energy density influences the choice. A battery can generally be charged with a speed proportional to the electricity supply speed (i.e. discharging). Charging of electric vehicles is still relatively new, and work is still ongoing to develop standards. An alternative to recharging the batteries is to have a surplus of batteries and replace empty batteries against charged when needed. This procedure is common for electric forklifts (Larsson 2012).

Batteries can store energy cheaper than supercapacitors and with higher efficiency. They are often combined with supercapacitors that have a longer life and power density, which, however, are less able to store energy. Battery development is subject to intensive research. Lead-acid batteries are used as the principal energy storage options in electric trucks, and electrical system for conventional vehicles. The disadvantage of lead batteries is the low energy density and the risk of forming hydrogen gas at electrolysis. NiMH batteries have higher energy density than lead batteries and contain no heavy metals. However, they are associated with memory effect where NiHM batteries gradually lose their energy capacity over time. Lithium-ion batteries are interesting because of their high energy density and a lack of memory effect and self-discharge. In order not to shorten the life of the battery, it is important that the battery is maintained at a suitable temperature.

Flywheels are used in conventional vehicles as an energy buffer, so that the mechanical energy of the combustion engine is spread out to avoid a rough and uneven behavior of the powertrain. Flywheels have a great strength in their ability to receive and deliver high performance.

Hydraulic accumulators can deliver very high power, but the energy density is low. To improve their use in mobile applications, there is ongoing research to increase the energy density.

Full electrification

Fully electrified machines have no tailpipe emissions, which makes the technology interesting from an environmental point of view and also from a health perspective. At the moment there are some ongoing projects which aim to electrify all or some of the machinery used at construction sites. One example of an attempt to make a working site fully or partly electrified is a research project that started in October 2015 and where Volvo Construction Equipment together with Skanska Sweden, a number of Swedish universities and the Swedish Energy Agency are working to get some of the machinery in an open-pit quarry partly or fully electrified. Due to differences in how different types of machinery are used, different solutions for making them electrified have to be considered. For example excavators and crushers that do not move around much can be connected to the electric grid by a cable. For more mobile units such as dumpers and loaders attaching a cable is not possible why a hybrid solution or fully electrification by using batteries is more suitable. During the project Volvo CE will be developing and testing the technologies, concept and prototypes in-house. Skanska Sweden will then incorporate the demonstration machines into its operations and test the electric site concept at a quarry in western Sweden, for 10 weeks at the end of 2018. After this, Volvo CE will examine the project results to see if the concept is viable for the industry. The project aims to transform the quarry and aggregates industry by reducing carbon emissions by up to 95% and total cost of ownership by up to 25%. The project is planned to finish in late 2018, (Volvo, 2016 and Andersson, 2015).

Hybridization applications

Mining

A wide range of machines, often specialized, are used in mining. Examples include bulldozers (to excavate soil), loaders (for the loading of broken material) and dumpers (for transporting the broken material). The special circumstances in mining means a number of special adjustments must be made (Larsson 2012). The machines tend to be much larger than in other areas. In some cases, electricity is supplied to the vehicle through a cable reel connected to the mains.

The Swedish industry enterprise Atlas Copco launched in 2016 a fully battery powered and fully automation ready underground loader (Scooptram ST7). The electric drive eliminates diesel emissions and the power cable, and minimizes the need for ventilation. According to the manufacturer, the energy consumption is reduced by about 80% compared to diesel machines. The underground loader is commercial available and the "normal size", machine weight measure is about 21.5 tons (Atlas Copco, 2016).

Fork lifts

Fork lifts are used to transport material short distances. They differ from other mobile equipment in that electrical powertrains have been used for over a century. Electric vehicles dominate the lighter segments (up to about three tons), while diesel vehicles handle heavier loads. They are generally used indoors and in specific sectors (for example in the food trade), where electric vehicles are the only permissible truck option (Larsson, 2012).

Spill-over from on-road technology

The cost of developing and validating fuel alternatives will limit the number of different non-road fuel types. Bergmann (2015) claims that the availability of engines from the on-road sector and the low prices of gaseous fuels in some regions will drive introduction of CNG and LNG. Biomethane is also one of the more promising alternatives for those sectors able to produce their own fuel from by-products and waste.

Conclusion

Cost and the profitability for machine users will be the deciding factor in determining the success of a mainstream alternative for fuel and technologies.

Providing the alternative fuels and the necessary powertrain concepts are not yet available for practical application, and many are still under various stages of development. The most important evaluation criteria for future fuel potential are deemed as:

- raw material and availability
- energy efficiency

- production technology
- technical maturity or stage of research and development

With regard to all criteria overall weighted, rapeseed oil fuel and biodiesel are considered as the best alternatives to diesel fuel in the agriculture and forestry sectors. It should be noted though that to fulfil the requirements of the diesel fuel standard EN 590 the fuel can only contain up to 7% biodiesel. Assessed as least advantageous, marked down by high costs, poor technical maturity and through missing infrastructure, was electrical drive with hydrogen fuel cells.

There is a limited demand for retrofitting of non-road machinery to ethanol, due to lack of technology for non-road engines for use with ethanol.

Ether-based substances such as DME or OME are not compatible with current fuel injection systems, although they are liquid when pressurized.

NG provides an interesting opportunity, as creation of the infrastructure offers potential to switch to biomethane in the future. Despite other disadvantages, NG is still interesting in those sectors that can produce their own biomethane from by-products and waste. Biomethane could be considered a positive alternative when looking towards a more sustainable agricultural sector. An important aspect is that NRMM that can use existing infrastructure for gas is better suited for the current marketplace; otherwise cost for new infrastructure has to be added.

Operational tests have shown that the dual fuel tractors have performed well. A conversion to dual fuel (methane and diesel) operation is better suited for entirely new machines than existing ones. The climate impact of dual fuel operation with biogas is estimated to be much lower than that of pure diesel operation (about 40%). The conclusion is that the technology has potential, but is not yet fully mature. Further investigations are required to gain a better understanding of emissions. Until there are regulations in place at an EU level, the current system of national exemptions is adequate.

Regarding hybridization or full electrification there are number possible options. These technologies have reduced or no tailpipe emissions, which make them interesting from an environmental perspective. In the available sources there are few judgements about the different potential for different alternatives. Still, some points may be mentioned;

- In Sweden, a research project is planned where the machinery in an open-pit quarry will be partly or fully electrified. Excavators are considered stable enough to be powered by wires, and crushers can also be powered by electricity. Dumpers could either be hybrids or electrified with a battery solution. The projection is that the energy consumption can be reduced with 70 percent in the future.

- An industry enterprise has launched a commercially available and fully battery powered and fully automation ready underground loader. The energy consumption is estimated to be reduced by about 80 % compared to diesel powered loaders.

- It is also important to mention that fully electrified fork lifts have been successfully used for over a century, though mostly indoor and for short distance transports.

Emission inventories and machinery models

Non-road emission models by country

Finland

Background

The TYKO model from VTT Technical Research Centre of Finland estimates emissions and energy consumption of non-road machinery, which are reported in the Finnish national inventories.

Format and use

The Finnish NRMM model consists of a database and calculation software (TYKO 2015). The database includes data on fleet, sales, powers, emissions and energy use during the years 1980 - 2040. Minor updates are done yearly and the model was last updated thoroughly 2013-2015. The calculation result is an excel file that consists of several sheets with numbers divided by machine types.

Model structure

The calculation model includes a fleet division by model year and power classes, and other machine characteristics. The model sums up the product of the machinery population, engine power, load factor, activity hours and emission factors. The calculation formula, which applies to all non-road machinery in the TYKO model, is presented below;

$$E_{v,t} = \sum_{l=1}^{44}\sum_{r=1}^{4} e_{l,r}\bullet g_{l,r}\sum_{t=1}^{40} k_{l,r,y}\sum_{m=1}^{40}\sum_{p=1}^{4}\sum_{u=1}^{3}\sum_{d=1}^{2} S_{l,m,p,r,u,d,t}\bullet a_{l,p,r,u,m,t,v,t}$$

where

Ev,t	total emissions v in year *t*
S	number of machines (population)
e	rated power
g	average load factor
k	activity (hours per year)
a	emission factor indexes
l	type of machinery
m	model year of machine
p	type of engine
r	power class (average rated power)
u	fuel type
h	average lifetime
d	type of usage (professional/leisure)
y	age of machinery
v	compound
t	calculation year

$$S_t = S_{t-1}\ \left(1 - w_t\right) + C_t$$

St	machinery population in year *t*
wt	wastage of machinery in year *t*
Ct	sales of machinery in year *t*

The machinery is divided into five main categories: drivable diesel, drivable gasoline, moveable diesel, moveable gasoline and handheld gasoline. Each main category has a number of subcategories, in all there are 51 machinery types. The intervals of the power classes differ somewhat, but are always 4. Consequently, with respect to subcategories (including fuel types) and power classes, fleet data can be entered for maximum of ca 180 different machine types separately. Emissions are calculated separately for gasoline, diesel and liquid petroleum gas (LPG) machinery.

The model includes today (2017) 8 different emission parameters (pollutants) which are CH_4, CO, CO_2, N_2O, NMHC, NO_X, PM and SO_2. Fuel consumption is also included and can be expressed in volume or energy. Also, it is possible to calculate the yearly consumption of AdBlue, which is a brand name for an aqueous urea solution used for SCR technology in diesel engines to reduce NO_X emissions.

Activity (h/y) is divided in two parts: active first phase and less active latter phase (normally half of the numbers of hours of active phase). For tractors, there is also a parameter describing the sector where the NRMM is used, four sectors are defined in the model; Farming, Industry, Maintenance and Other.

The calculation method is in general consistent with the IPCC Guidelines (corresponds to the Tier 3 level method). The method is widely used, for example, in the U.S. EPA Non-road model (1998) and CORINAIR Off-Road vehicle and Machines model (Andrias et al., 1994). The emission factors of CH_4 and N_2O have been harmonized to comply with the 2006 IPCC Guidelines and EMEP/EEA 2013.

Data sources in general

Data on machine population are based on national estimations, machinery registrations, sales figures and knowledge on the life expectancy of machinery. The activity data in TYKO are based on national and international research.

Result

The Finnish model is able to estimate national emissions from NRMM per pollutant and year. The model is not able to generate emission data by sector (except for tractors) and neither separated by power class. The main results of the TYKO model can be seen on the website: http://lipasto.vtt.fi/en/tyko/index.htm.

Germany

Background

Official reporting obligations for emissions from NRMM in Germany are fulfilled by the German Federal Environment Agency (Umweltbundesamt, UBA). The Institute for Energy and Environmental Research (ifeu) has developed a differentiated inventory model to fulfill the obligations. This model complemented the already existing model TREMOD (Transport Emission Model) for the transport sector and is referred to as TREMOD MM (MM for Mobile Machinery). This chapter about the German model is completely based on the document *The Mobile Machinery Emission Inventory in Germany - Documentation and Results.* (Helms & Heidt, ifeu, 2017).

Format and use

TREMOD MM is a Microsoft Access based tool considering the structure of current emission regulation, taking into account highly differentiated and transparent input data; future emissions can be calculated by using different scenarios. Main input data for TREMOD-MM are updated annually on behalf of the Federal German Environment Agency (UBA). Further development of methodology, machinery and pollutant coverage is undertaken as projects at irregular intervals, depending on the legislative, political and industry requirement.

Model structure

TREMOD MM basically uses the so called "population method" (Tier 3 method), which is also internationally established for the calculation of emissions from mobile machinery. A similar approach to calculate fuel consumption and exhaust emissions of several pollutants from non-road equipment and machinery is used in Switzerland, the United States (EPA NON-ROAD model) and other European states. TREMOD MM can be used for estimating emissions in Germany from 1980 till now and also for making scenarios until 2030.

The model includes land based NRMM but also machinery for waterways (recreational boats) and railways. Included are for example, machinery used in agriculture, construction, household and gardening (private and professional) and other sectors like industry.

Emissions are calculated via stock, activity and emission factors using the equation below:

$$EE = N \times P \times \mathrm{HRS} \times LF \times EF$$

where

EE = Exhaust emissions (of one layer, e.g. emissions from agricultural tractors, model year 2010 with 37-75 kW in 2015)

N = Number/Stock of machinery/devices/vehicles

P = Average Power (of this layer)

HRS = Average operational hours

LF = Typical load factor (<1)

EF = Emission factor (g/kWh)

The model structure is buildup by certain parameters with limited number of categories. It has five main parameters which are Sector, Machinery type, Power class, Emission standard and Fuel type. Certain categories in one parameter normally fall under certain categories in another, but generally the parameters are independent. However, all combinations do not exist in reality and consequently are not appearing in the model.

To adapt these emission data to the real behavior in TREMOD MM, adjustment factors for the aging (deterioration factor = DF) and dynamic behavior (transient adjustment factor = TAF) are used. TAF is calculated according to the formula below:

$$TAF\ [-] = \frac{\mathrm{Emission}_{transient}\ \mathrm{in\ gkWh}}{\mathrm{Emission}_{\mathrm{stationary}}\ \mathrm{in\ gkWh}}$$

Furthermore, evaporative and refueling emissions are considered. Thus total emissions are calculated as follows:

$$ET = EE + EV + ER$$

with:

ET: Total emissions

EE: Direct exhaust pipe emissions

EV: Evaporation emissions (only hydrocarbon)

ER: Refueling emissions (only hydrocarbon)

Today (2017) the model includes 12 different emission parameters (pollutants) which are BC, CH_4, CO, CO_2, HC, N_2O, NH_3, NMHC, NO_X, PM, PN and SO_2. FC (fuel consumption) is also included.

Data sources in general

This section provides an overview of the most important data sources with a particular focus on the agriculture and construction sector. The data quality may vary much between the sectors.

Detailed statistics of stock data are only available for agricultural tractors on the part of the KBA. For the remaining stock data, either association statistics (e.g. Forestry) were used or a calculation was made based on sales numbers (e.g. Construction and Industry, Household / Gardening). Regarding the use of the equipment (annual operating hours), various used machinery resale platforms have been evaluated and analyzed[2]. Industry data are analyzed as well and are retrieved from the hour counters of the machinery stock of companies. The values have been compared to the input

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[2] http://www.machineryzone.de/; http://www.bau-portal.com/

data used e.g. by the Swiss BAFU, EPA or European Commission Joint Research Centre (JRC).

The basic emission factors are not machinery specific but depend on the fuel type, power class and emission Stage of the engines. In the case of diesel engines up to Stage II, extensive data were evaluated (for gasoline engines up to stage I), which were compared to literature values from other countries. From Stage IIIA onwards (for petrol engines from stage I), the estimation of the emission factors are based on the emission limit values set by the European emission standards and expert judgment.

Data sources agriculture

In agriculture, mainly diesel-driven tractors and combine harvesters are used as motorized machines. The forestry tractors used exclusively in forestry are considered in the "forestry" sector.

The German Federal Motor Transport Authority (KBA) regularly collects stock data for tractors, which are differentiated by registration year and power class. Retrofitted tractors, which are registered in the KBA statistics under tractors, are often also used in forestry (1% of stock). Data on the stock of combine harvesters are based on data from the Federal Statistical Office.

The operating hours were determined by means of an elaborate procedure by evaluating used machinery resale platforms. Machines of a higher power class are used significantly more than low-power engines. Load factors are mostly based on the data from the Swiss NRMM Model (BAFU, 2015).

Data sources construction

In the construction industry, machines are used for road construction and civil engineering. Most of these are diesel-operated and only a few use other fuel types. Trucks used in the construction industry are within the TREMOD structure, taken into account in the road transport sector. Cranes, pumps, welding equipment and cooling units have for the most part an electric drive and therefore do not contribute to air pollution emissions. Generators and forklifts are considered in the industrial / other sector.

Data on the construction machines are based on the Statistical yearbooks of the Federal Republic of Germany (FRG) until 1996, the further inventory development up to 2010 is based on the population numbers from the British consulting company Off-Highway Research (2011), and the production and foreign trade statistics of the Federal Statistical Office of Germany. After 2010, extrapolation of the past trends was adopted. Annual operating hours is based on counters that are installed in most of the larger construction machines, and data has been deducted from a used machinery platform and companies (only machines in Germany). The annual operating hours are however corrected by reference years to adjust to cyclical fluctuations, and a price-adjusted index of the turnover in underground construction is used.

This index fluctuated by about 30% over the last twenty years, and has fallen since the mid-1990s. Since an increase in the number of machines has taken place in most categories, an adaptation was considered to be plausible in order to reflect the economic development. The shares of stock on the different power classes and the average performance per class are also based on company data.

Data sources other sectors

The machines used for forestry are large forestry machines for harvesting timber and hand-held motor or chain saws. Smaller work such as transport and maintenance in the forest are usually carried out by tugs. The data is from a machine survey carried out by the Board for Forestry and Forestry Technology (KWF) and is based on sales figures. Large machines in forestry are exclusively diesel-powered and have small stocks; additionally there are a large number of hand-held power saws equipped with Otto engine. The operating hours and load factors are based on data from Swiss Bundesamt für Umwelt (BAFU, 2008), and a correlation is also made with the wood production.

In the household and gardening sector, mainly gasoline- and electric-powered appliances are used. These devices generally have lower operating hours but stock numbers are high. There are also many professionally used devices with significantly higher operating hours. Private stocks and different types of professional use of the same machine type are therefore treated as different machine categories.

The machine stock in the household and gardening sector is derived from sales figures and the estimated life span (European inventory statistics, JRC, 2008). The operating hours and load factors again are based on data from Swiss Bundesamt für Umwelt (BAFU, 2008).

In the field of industry/other, generators and forklifts are considered which are generally operated with diesel fuel, some forklifts also use LPG. The stock was estimated on the basis of industry data, and sometimes production figures, import, export and scrapping data.

Sweden

Background

Official reporting obligations of emissions from NRMM in Sweden are fulfilled by the Swedish Environmental Protection Agency. The model that is used to fulfill the obligation was originally developed with the main objective to estimate fuel consumption and emissions from NRMM for year 2006 (Lindgren, 2007). The model has later on been adapted to fulfill the obligations of the reporting to UNFCCC and CLRTAP

Format and use

The model is fit into an Excel workbook and uses both Excel formulas and VBA (Visual Basic for Applications) code for calculations. The modeled results are mainly used for Sweden's annual reporting of greenhouse gas emissions to the UNFCCC and of air pollutants to the CLRTAP.

Today no agency has the official responsibility to manage and update the model. Due to this fact, there is no plan of e.g. how often the model should be updated or what kind of functionalities the model should have. The only update that is decided to be done on yearly basis is the populations of tractors and snow mobiles which are obtained from the Swedish vehicle register. These updates are done by IVL Swedish Environmental Research Institute and financed by the SEPA. Other development of the model and updates of data is undertaken as projects at irregular intervals and have so far been financed by either the STA or the SEPA. However, the updates have not always been well harmonized and there is at the moment a need for a plan of how to keep the model updated in the future. Some of these needs are addressed in a project running during 2017 but there will after that still be a need for a long-term plan of how to keep the model up to date.

Model structure

The model is considered to correspond to Tier 3 according to the 2006 IPCC Guidelines (IPCC, 2006). The approach is similar to that used by e.g. Germany and Switzerland. The model includes all NRMM excluding those used on waterways and railways. Included are for example, diesel machinery used in agriculture, construction and mining, spark ignited machinery for lawn and garden, snow mobiles and terrain vehicles. The model calculates fuel consumption and exhaust emissions of several pollutants from 1990 till now and in scenarios until 2030. It is prepared for including machines running on RME (Rapeseed methyl ester), methane, dual fuel (methane and diesel), ED95 and E85. However, when using the model for making emission estimates today all machinery are assumed to be running on diesel or gasoline. Also, the level of low blended components in the diesel and gasoline can be defined in the model.

Emissions and fuel consumption are calculated using the equations below:

$$EE = N * P * HRS * LF * EF_{adj}$$

where

EE = Exhaust emissions (of one layer, e.g. emissions from agricultural tractors, model year 2010 with 37-75 kW in 2015)

N = Number of vehicles

P = Average engine power in kW

HRS = Average yearly running time in hours

LF = Typical load factor

EF_{adj} = Emission factors in g/kWh adjusted according to the equation below

$$EF_{adj} = EF_i * CAF * TAF * DF * FAF$$

EF_i = Emission regulations according to EU legalization in g/kWh or emissions factor from another source e.g. EEA (2007).

CAF = Adjustment factor for difference between regulation and value measured at certification.

TAF = Adjustment factor for transient (i.e. difference between static test cycle and real use of the machine).

DF = Adjustment factor for decline of the motor by increasing age.

FAF = Adjustment factor for difference between certification fuel and Swedish “Miljöklass 1” (environmental class 1) diesel.

The model structure is buildup by certain parameters with limited number of categories. The Swedish model has four main parameters which are sector, machinery type, power class and fuel type. For gasoline powered smaller off-road vehicles and machinery, engine type (two/four - stroke etc.) appears as a fifth parameter. The emission standard is not a parameter itself, but influences the estimated fleet composition (and emission factors) from year to year due to the introduction of new legislation. Certain categories in one parameter normally fall under certain categories in another, but generally the parameters are independent. However, all combinations do not exist in reality and consequently are not appearing in the model.

Today (2017) the model estimates emissions of 12 different emission parameters (pollutants) CH_4, CO, CO_2, N_2O, NH_3, NMVOC, NO_X, TSP, PM2.5, PM10, BC and SO_2. Also, FC (fuel consumption) is estimated. No evaporative or refueling emissions are considered.

Data sources in general

This section provides an overview of the most important data sources. The sub sections are divided into machinery categories that share the same data sources. The data quality varies much between the groups but also for different machine types within the same group. Emission factors are presented in a common section including all machine types.

For machine types where stock data is not obtained annually the stock has been estimated for one or two years within certain studies. For estimating the stock following years an equation is used to calculate the number of machines that will be scrappaged from the year before (USEPA. 2005a). Also, sales numbers of new machines have been obtained for some machine types which have been used to estimate the population.

Data sources - emission factors and fuel consumption

Emissions of CO_2 and SO_2 are estimated from the modeled fuel consumption and the carbon and sulphur content in the fuels respectively. The emission factors for CO_2 and SO_2 are adjusted according to fuel specifications for each year.

Emission factors for diesel machinery with an installed engine power between 37 kW and 560 kW are based on the emission regulations according to the EU legislation. The fuel consumption for this power range is taken from Lindgren (2007) which are derived from EEA (2005). Emission factors for diesel machinery < 37 kW are taken from EEA (2007).

The fuel consumption for these machines is from the Danish Ministry of the Environment (2006). For gasoline powered machinery, emission factors and fuel consumption are in most cases also taken from the Danish Ministry of the Environment (2006). These are based on certification measurements. Fuel consumption and emission factors for snow mobiles are also taken from the Danish Ministry of the Environment (2006), except the emission factors for hydrocarbons, carbon monoxide and particles, which are taken from USEPA (2005b).

The fuel adjustment factor, FAF, and the certification adjustment factor, CAF, for larger vehicles are taken from Lindgren (2007). The TAF and DF factors are taken from the USEPA (2010a, 2010b).

All emission factors and fuel consumption for Stage V machinery are set as the emission limits for this Stage.

Data sources - tractors

Stock data is updated annually by using data from the vehicle register provided by the Swedish Transport Agency. In the register the tractors are differentiated by registration year and engine power. There is also a differentiation on the sectors agriculture/forestry, industry, commercial/institutional and residential. For all other parameters, i.e. average power, average load factor and average operating hours data from Lindgren (2007) are used.

Data sources - forestry and agriculture

This group includes most machines used in agriculture and forestry excluding tractors and some machines with an installed power > 560 kW. All used input data are taken from Lindgren (2007).

Data sources - construction

Estimates of the vehicle stock are mainly based on Lindgren (2007) and Jerksjö (2013). Both sources presents estimates of the stock estimated from the number of inspected machines at the Swedish machinery testing institute and also sales numbers. The estimates are for year 2006 and 2012. Average power, annual working hours and load factors are taken from Lindgren (2007). An exception is load factors for wheel loaders (75-560 kW), crawler excavators (37-560 kW) and articulated haulers (130-560 kW) which are taken from IVL (2014a). These load factors were obtained by using data logged by machines from two major manufacturers during normal operation.

Data sources machinery >560 kW

Calculations of emission from machinery >560 kW was added to the model in 2015. These machines are mainly wheel loaders and trucks used in the mining industry but there are also a few machines used in agriculture and also some mobile generators. Data is from IVL (2014b) and were mainly obtained by contacting organizations using these kinds of machines to get an estimate of the number, annual operation hours and power. The load factors were estimated by IVL.

Data sources - garden machinery and other machinery < 36 kW

Machines used for gardening and also smaller machines used in e.g. construction work is the group where least is known about stock, operating hours, and load factors. Information on the stock is mainly based on the last national inventory of these machines which estimated the machinery stock of year 2002, Flodström *et al.* (2004). Used average power, load factors and operating hours are to large extent also from this report. Some information is also taken from Jerksjö (2014). This study included a survey directed at households with the aim to estimate the national number of some gardening machines owned by households and also the yearly operating hours and fuel consumption. Operating hours for professionally used lawn mowers were also estimated in this study by contacting some professional users. Also, sales figures from a trade organization have been used to estimate the stock.

Data sources - snow mobiles and terrain scooters

Stock data is updated annually by using data from the vehicle register provided by the Swedish Transport Agency. Data on variations in annual operating hours as a function of age are from the International Snowmobile Manufacturers Association through Peters (2007). The data has been adapted to average annual operating hours presented in Edin (2007). Median load factors are from USEPA (2010c).

Comparisons of models

Differences between models

The Swedish, Finnish and the German models use a Tier 3 bottom-up approach (IPCC, 2006) and are very similar in structure and method. The main difference may be the use of different software platforms.

The Finnish model has a few important differences compared to the Swedish and German models. There is no defined categorization of the machine types by sector (agriculture/forestry, construction, industry, household/commercial), even though many machine types clearly can refer to a specific sector based on its characteristics.

The Finnish model compared to the Swedish model has in general a more detailed categorization of smaller power classes; on the other hand, larger machines than 130 kW cannot be separated (applies to all machine types).

The Finnish model is not able to automatically generate emissions values separated by power classes; instead an average engine effect is calculated per machine type based on the fleet composition and the load factors (which may differ between categories).

Recreational boats and railways are not included in the Swedish and Finnish models, unlike the German.

Comparison emission shares

Figure 8 present a comparison of NO_X-emission shares (%) between the German and Swedish model. Numbers presented are divided by sectors, power classes and fuels.

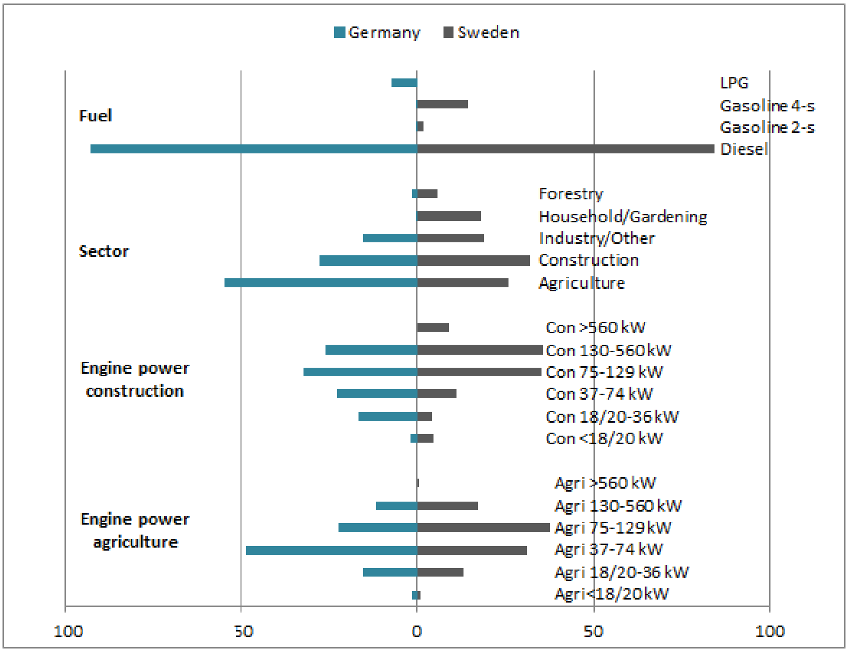

Figure 8. Comparison of NO_X-emissions between German and Swedish models, with respect to fuel type and sector. The figure also shows the internal relation between power classes within the construction sector and Agricultural sector. Bars represent share (%) of national NO_X-emission.

The comparison in Figure 8 illustrate relatively similar emission patterns in Sweden and Germany, however, there are also significant differences. The differences with respect to sector may mirror the two countries geography and economies. Germany has a large agriculture sector, and NO_X-emission from agriculture machines is dominant. Sweden on the other hand, with large areas of forests and more vast physical landscapes and sparser urban areas, has relatively speaking higher emissions from forestry, households and gardening (including commercial activities). Relative NO_X- emissions from industry and construction sectors are very similar in both countries.

When analyzing NO_X-emissions with respect to power class distribution the two countries are relatively similar for both the agriculture and the construction sectors. Sweden has in general somewhat larger machines. When it comes to fuel type, both countries are unsurprisingly totally dominated by diesel, though an interesting difference is that gasoline represent an 18% share in Sweden but is totally negligible in Germany (ca 0.3%). Instead, Germany has introduced use of LPG which constitutes almost 10% of NO_X-emissions. For other pollutants like CO and HC, gasoline is still responsible for > 50% of the emissions also in Germany (not shown in diagrams).

Figure 9 presents a comparison of emission of HC, CO, CO_2 between the German and Swedish models divided by sector.

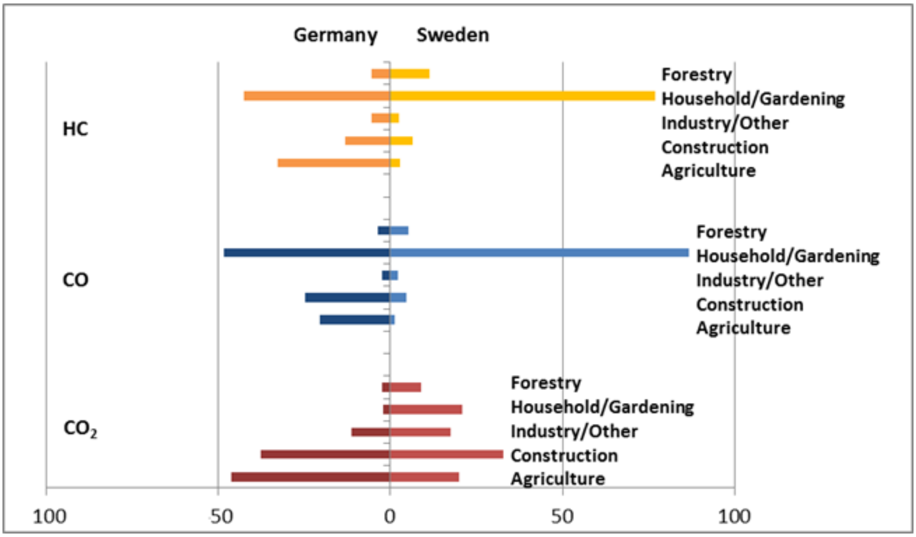

Figure 9. Comparison of HC, CO and CO_2-emissions between the German and Swedish models, by sector. Bars represent share (%) of national emissions.

The CO_2-figure is very similar to the NO_X-figure in the previous diagram, while HC and CO emissions are very similar in both countries but different from NO_X/CO_2. In both countries, the sectors household/ gardening are standing out with respect to HC and CO, but in Sweden its dominance is total. This mirrors the very high usage of gasoline in smaller machines in this sector compared to Germany.

It is not possible to compare the Finnish model with the Swedish and German models in this aspect, due to insufficient definition of the "sectors" in Finnish model as explained earlier. Instead, the modeled emission shares in Finland are presented in the Figure 10 divided by its four main machine categories;

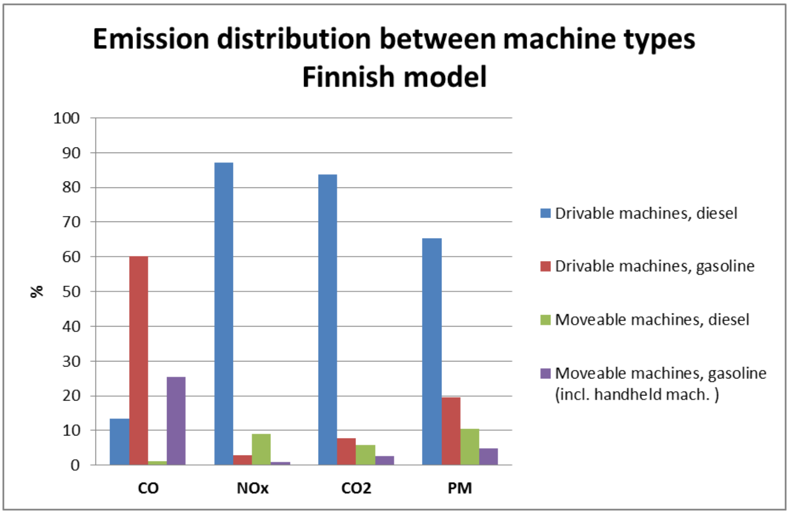

Figure 10. CO, NO_X, CO_2 and PM-emissions from the Finnish TYKO model by main machine categories. Bars represent share (%) of national emission.[3]

If comparing emissions in absolute numbers between the NRMM-models in Finland, Sweden and Germany, the levels of emission parameters from combustion engines like NO_X and CO_2, may be expected to have about the same relations as the countries' population size (1, 2, 16), (economic parameters are assumed to be the same). But the comparison reveals that if taking differences in populations into consideration Sweden has higher emissions than Germany, about the double amount regarding CO_2 and a factor 1.5 for NO_X. What is even more remarkable are Finland's very high emissions compared to its population. Finland's emissions are almost in the same level as Swedens's but with the half population, and a factor 2,3- 2,6 compared to Germany. The unbalances between the modeled emissions in the three countries cannot be explained without detailed analysis of the input

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[3] NMHC emissions are missing, the data was not available due to technical problems.

data, like emission factors, machinery populations, activity data etc. However it is important to clarify, it is not possible to draw any conclusions about the models reliability, data coverage or other quality aspects without mentioned analysis. This comparison is shown in Table 2:

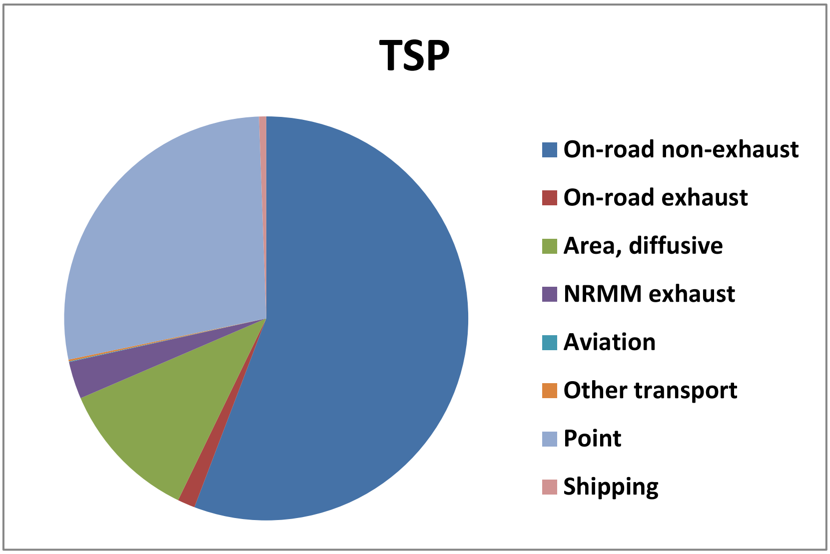
Table 2. Absolute emissions of NO_X and CO_2 in kilotonne and their relations to each other in Finland, Sweden and Germany.

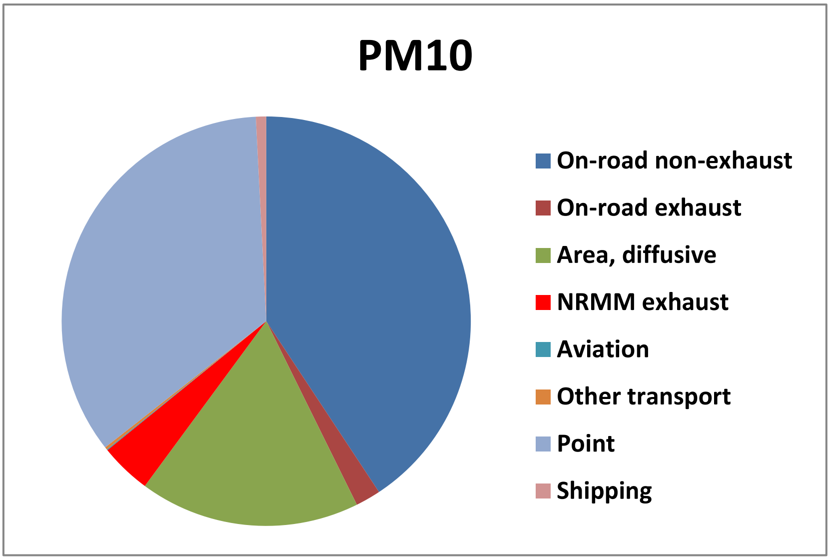
	Germany	**Sweden**	**Finland**
NO_X	98.4	16.7	14.5
CO_2	14800	3600	2414
Relation NO_X	1	0.17	0.87
Relation CO_2	1	0.24	0.67
Relation NO_X – normalized to population	1	1.4	2.4
Relation CO_2– normalized to population	1	1.9	2.6

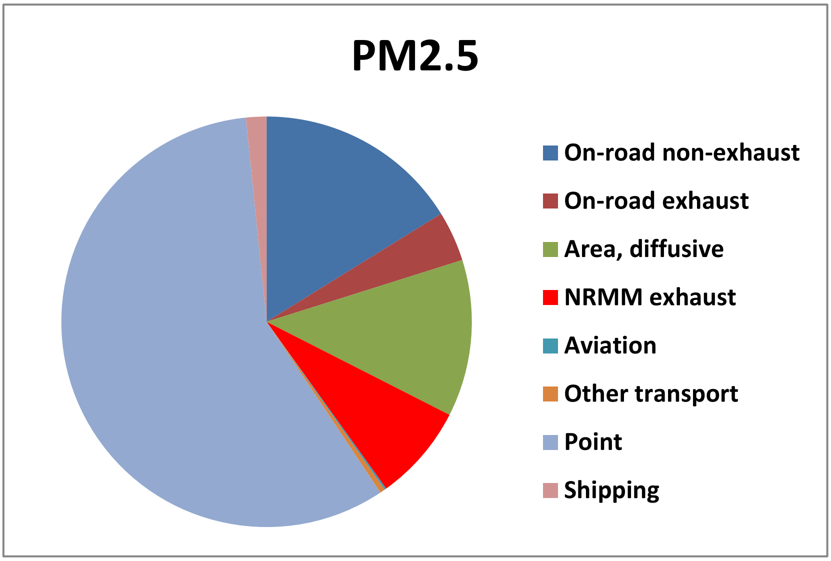
National calculated emissions

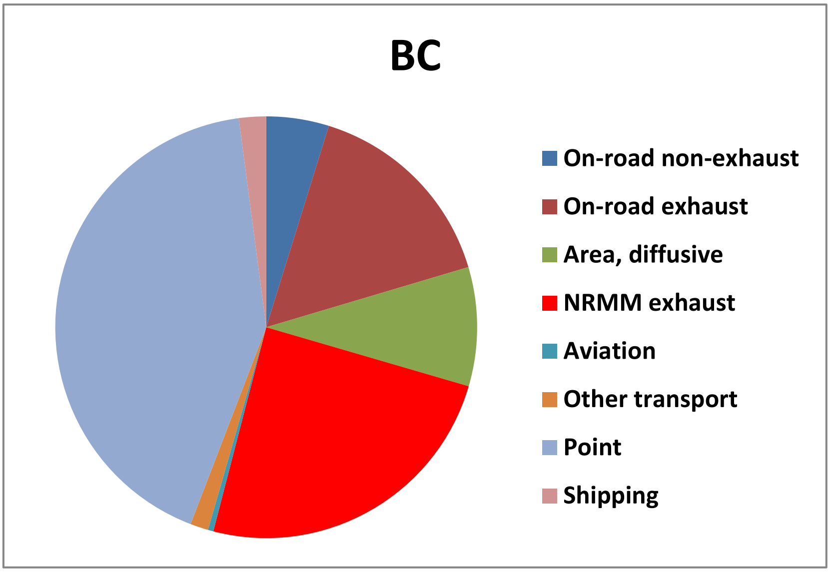
Sweden

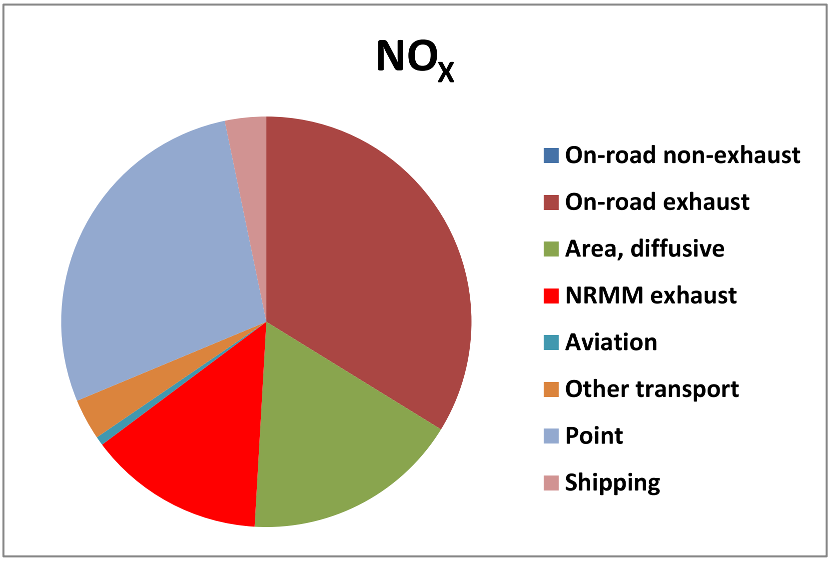
Figure 11 presents' national air emissions from NRMM and its shares compared to other main sectors (numbers refer to year 2015).

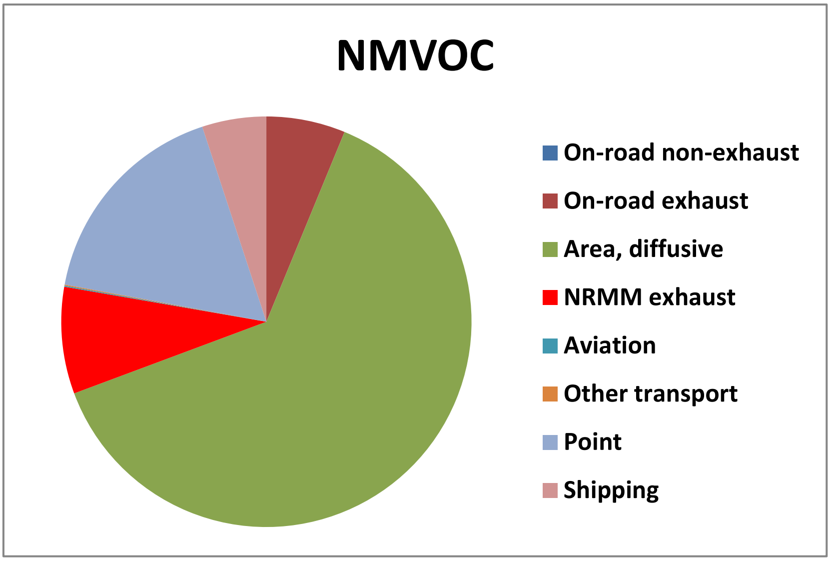


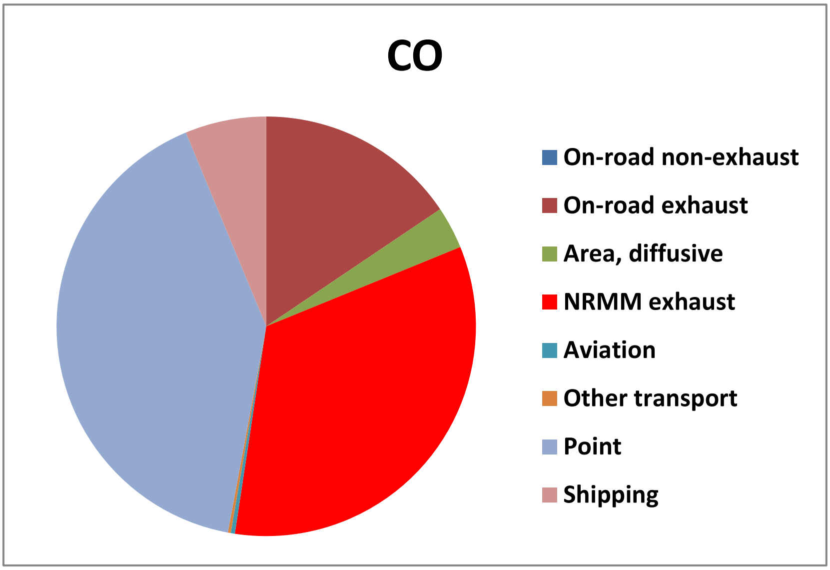

PM10
On-road non-exhaust
On-road exhaust
Area, diffusive
NRMM exhaust
Aviation
Other transport
Point
Shipping

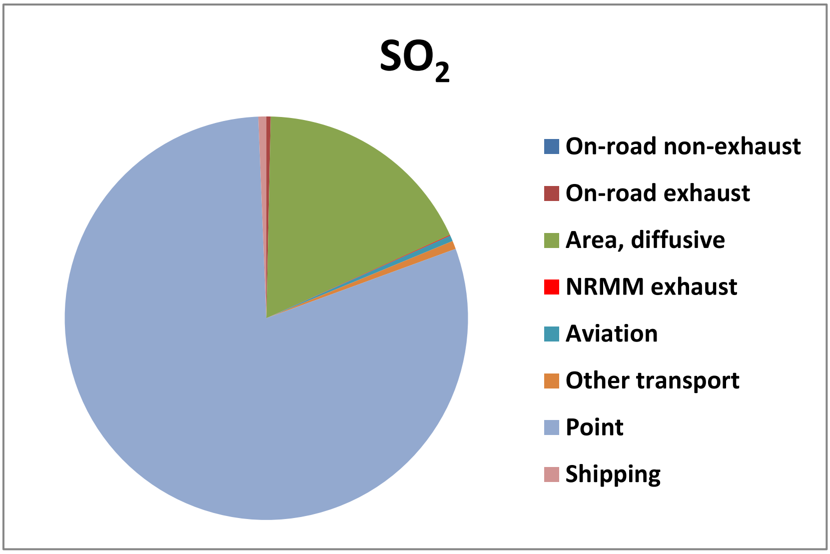

PM2.5
On-road non-exhaust
On-road exhaust
Area, diffusive
NRMM exhaust
Aviation
Other transport
Point
Shipping

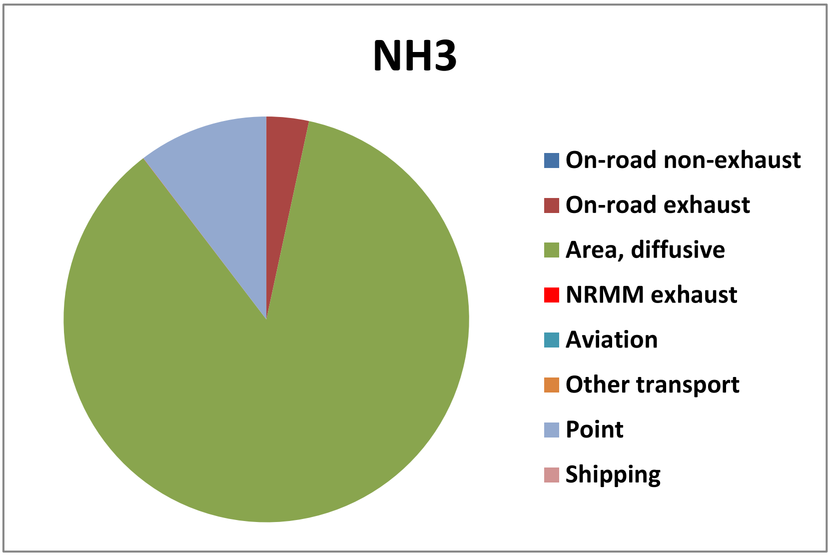

BC
On-road non-exhaust
On-road exhaust
Area, diffusive
NRMM exhaust
Aviation
Other transport
Point
Shipping


NO_X
On-road non-exhaust
On-road exhaust
Area, diffusive
NRMM exhaust
Aviation
Other transport
Point
Shipping


NMVOC
On-road non-exhaust
On-road exhaust
Area, diffusive
NRMM exhaust
Aviation
Other transport
Point
Shipping


CO
On-road non-exhaust
On-road exhaust
Area, diffusive
NRMM exhaust
Aviation
Other transport
Point
Shipping


SO_2
On-road non-exhaust
On-road exhaust
Area, diffusive
NRMM exhaust
Aviation
Other transport
Point
Shipping


NH3
On-road non-exhaust
On-road exhaust
Area, diffusive
NRMM exhaust
Aviation
Other transport
Point
Shipping

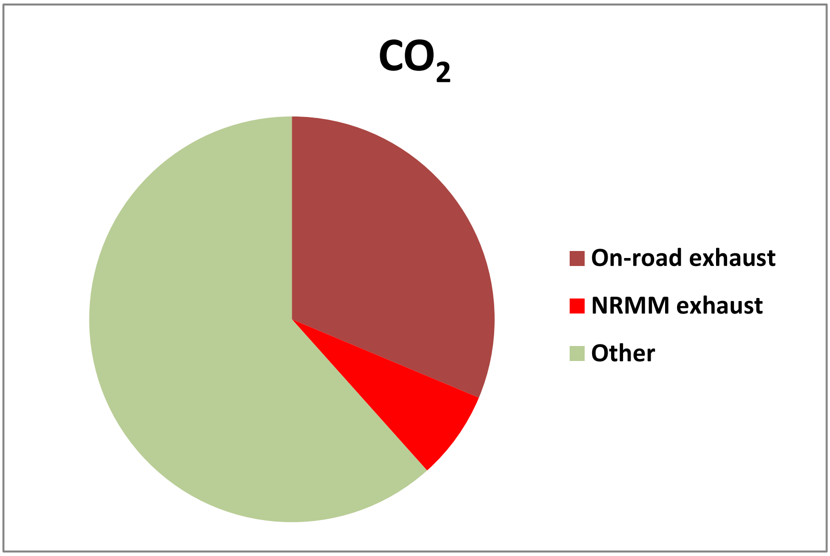


Figure 11. National air emissions (TSP, PM_{10}, $PM_{2.5}$, BC, NO_X, CO, NMVOC, CO_2) in Sweden 2015 from NRMM compared to other main sectors (SMED, 2017).

NRMM contributes to about 6.7% of the national CO_2-emissions in Sweden.

Regarding air pollutants the pie charts clearly show that NRMM (clear red color) contribution is significant for several of the most important pollutants. NRMM has greatest impact for exhaust-related emissions like NO_X, CO and BC and make up about 15-30% of these pollutants of the national total. When it comes to particulates in different size ranges, NRMM contributes negligible to the total dust emissions (TSP), however, its contribution to the smaller particles ($PM_{2,5}$), which is believed to have the most serious health effects- is not insignificant (ca 8%). BC, which recently received increasingly attention internationally and which from a health perspective is considered as one of the most important air pollutants, NRMM is estimated to be responsible for about 25% of the national emissions in Sweden.

(One could point out that NRMM while working also causes non-exhaust emissions from various movements in analogy with wear/resuspension from road traffic, and therefore NRMMs contribution to particulate emissions is underestimated. Anyhow, those emissions are in this presentation included in the fraction “Area, diffusive” and are difficult to quantify).

Comparison of NRMM emissions versus on-road emissions for Sweden and Germany

Comparison of non-road and on-road emissions in Sweden and Germany, with respect to NO_X, PM2.5, CO and HC, are presented in Figure 12.

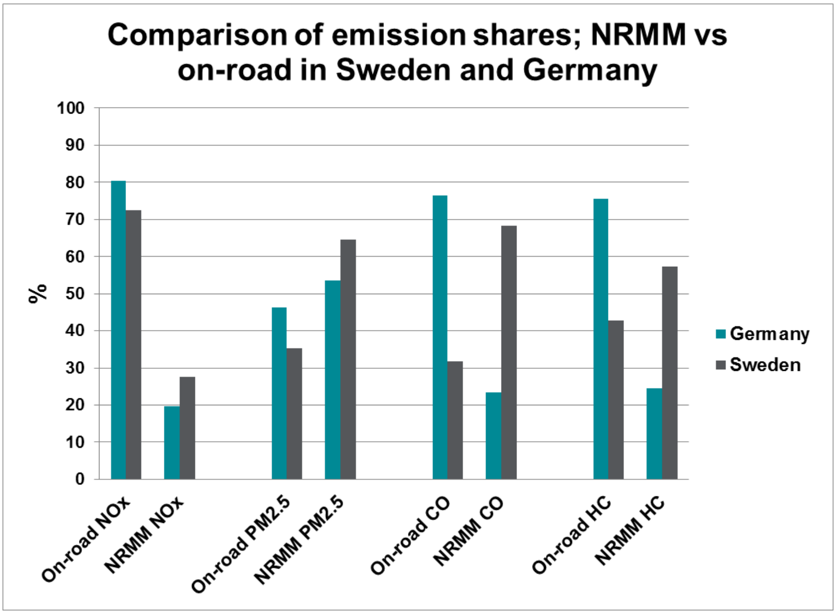


Figure 12. Comparison of the relation of non-road and on-road emission in Sweden and Germany (NO_X, PM2.5, CO, HC).

Sweden and Germany have similar shares of on-road and NRMM emissions when it comes to NO_X and $PM_{2.5}$, but for CO and HC, the shares from NRMM are considerable higher in Sweden then Germany. This is explained as Sweden use relatively more gasoline, which normally is concentrated to smaller machines used in households and commercial sectors, for example snowmobiles and other recreational equipment. Only snowmobiles constitute about 25% of the total CO-emissions from NRMM in Sweden, and their share of HC is even higher (snowmobiles for private use are banned in Germany).

Conclusion

The three countries models are similar and basically based on the same methodology. All three fulfill the requirements to supply high quality and differentiated emission data for a number of pollutants, among others used in international reporting.

One important aspect which is applicable to all three countries is that emission factors from Stage IIIA and onwards, are estimations based on the limit values set by the European emission standards and on expert judgments. Taking into account that NRMM in general has considerable higher emission uncertainties then on-road vehicles, may lead to the conclusion that there is a significant need for more real-life emission measurement to verify and improve the estimations of the emission factors. This aspect is very important since NRMM constitutes to relatively large portions of the national emissions, which is especially true when it comes to pollutants like CO and BC.

While the model structures and parameters are similar, data sources for e.g. population, ageing, load factors and sector classifications vary considerably and are inconsequent between and sometimes even within countries. Other aspects to consider are data coverage and activity data. Standardization regarding use of data sources, data collection and updating methods between the different countries and other similar issues is desirable.

The analysis of the absolute emission levels in Finland, Sweden and Germany also indicates possible unbalances in calculation methods, data coverage, collection of data etc., which identifies a need for deeper comparisons of the models.

National non-road policy options

Introduction

NRMM are in general subject to less legislation than road vehicles. There are also fewer policies targeting NRMM emissions of energy and fuel efficiency. Existing policies affecting NRMM can be divided into general policy instruments, including but not targeting NRMM, and policy instruments that specifically address NRMM.

A general policy could include fuel taxes or low-emission zones applicable for both NRMM and road vehicles. NRMM specific policies include emission standards for NRMM, mandatory exhaust cleaning equipment such as particle filters, public procurement requirements on construction machines or grants for replacing older machinery by newer and more efficient ones.

Non-road policy options in different countries

Germany

General

NRMM in Germany is subject to the European emission regulation specified in Directive 97/68/EC and several amending Directives. For diesel machinery, so far Stage I to IV have been introduced and Stage V (Regulation 2016/1628) will become effective from 2020. The EU regulation only covers pollutant emissions; so far no regulation of CO_2 emissions for mobile machinery is on the way.

The agricultural sector has the highest share on mobile machinery diesel fuel consumption and is being largely operated out of urban areas. Therefore further national policies for the agricultural sector rather focus on the use of alternative fuels and thus target CO_2 emissions. The construction sector on the other hand, is also making a relevant contribution to urban PM_{10} and NO_2 concentrations (ifeu, 2014a; ifeu, 2014b). Therefore, regional and local measures focus on the use of after treatment systems and early introduction of clean emission standards.

Agricultural sector

The main alternatives to (fossil) diesel fuel in the agricultural (and forestry) sector are biodiesel or vegetable oils. These are subject to different international and national regulations. On the EU level, the Renewable Energies Directive (EU, 2009) and the Fuel quality directive (EU, 2012) apply. On the national level, the use of biofuels in agriculture is generally supported by the German Energy Tax Act by an almost complete refund of the energy tax.

The resulting advantage, however, is considerably reduced by a general partial refund of the energy tax for diesel fuels used in agriculture (shown in Table 3). According to KTBL (2013) therefore currently no competitive advantage for the renewable fuels biodiesel FAME.

Table 3: Diesel taxation in Germany (Energy Tax Act §57 (Bundesregierung, 2017)).

	Fossil diesel (road)	**Fossil diesel (agriculture)**	**Biodiesel (agriculture)**
Refund cent/litre	N/A	21.48	45.03
Energy tax cent/litre	47.04	25.56	2.01

Further incentives are given on the level of several federal states (Bundesländer). Most notably the program RapsTrak200 by the Bavarian Ministry for Economic Affairs provides funding for the use of plant oils in order to increase the use of rapeseed oil and plant oil fuels in modern agricultural and forestry tractors and other mobile machinery. Funding is available for the following:

- New acquisitions of tractors and mobile machines of the exhaust Stages IIIB (until 2016-03-31) and Stage IV (until 2017-21-31), which are standardized for operation with rapeseed oil fuel
- Retrofitting of tractors and mobile machines of the exhaust Stages IIIB (until 2016-03-31) and Stage IV (until 2017-12-31) for operation with rapeseed oil by authorized workshops

The funding is provided as share financing through non-repayable grants (promotion of projects). The subsidy rate is 80% of the eligible expenditure, but a maximum of 7,500 € per measure. If grants or investment subsidies are granted from public funds of the federal or state government for the same funding purpose, funding under this Directive is excluded.

The state government of North Rhine-Westphalia (Nordrhein-Westfalen) is promoting a pilot and demonstration project for the use of domestic vegetable oils in agricultural mobile machinery. The aim is the demonstration of the full suitability of the tractors and significant reductions in greenhouse gases and at the same time increased contributions to domestic protein supply (NRW, 2015).

Construction sector

While national policies for the agricultural sector focus on the use of alternative fuels, national and regional measures for the construction sector focus on pollutant emissions and target the use of aftertreatment systems and the early introduction of clean emission standards. Since construction machinery in Germany is subject to the European emission regulation, the emission Stages provide a categorization of the emission level which can be used for local measures.

While the emission regulation at European level only regulates the approval of engines in new machinery, national measures are often also targeting the reduction of emissions in the machinery stock, e.g. by retrofitting.
Role model for Germany regarding obligatory use of "diesel particle filters" (DPF) was the ordinance on air pollution control in Switzerland. Since 2010, new construction machines ≥18 kW had to comply with a particle number limit of $1*10^{12}$ at all construction sites, which requires the use of a particle filter. Older machinery of ≥37 kW had to be fitted with particle filter systems compliant with the air pollution control ordinance.

In Germany until 2013 only machinery in tunnel and underground construction had to be equipped with particle filters. The requirements according to the "Technical Rules for Hazardous Substances" (TRGS 554 and TRGS 900) apply for these works. In the last few years, however, individual players have increasingly been using "clean" machines on construction sites. Examples are urban construction sites of German Railway (Deutsche Bahn) and the large-scale construction site "Stuttgart 21". Now also some municipalities and federal states have moved on and introduced further local requirements for use of construction machinery in urban areas.

Construction machinery used for works within municipal tenders of the City of Berlin (Berlin Senate) need to comply with at least the following emission standards of the Directive 97/68 / EC:

- ≥ 19 to < 37 kW: Stage IIIA (or diesel particle filter)
- ≥ 37 kW: Stage IIIB (or diesel particle filter)

Construction machinery purchased by the Berlin Senate need to be equipped with a particle filter and comply with at least Stage III A ≥ 19 to < 37 kW), Stage III B (≥ 37 kW to < 56 kW) and Stage IV (≥ 56 kW). Similar requirements for construction machinery used for works within municipal tenders have been introduced by the City of Bremen and became effective in 2016.

On the level of federal states, Baden-Württemberg has adopted an air quality ordinance for construction machinery for selected municipalities (currently Ludwigsburg, Reutlingen, Tübingen, Markgröningen and Stuttgart), which specifies first requirements from 2017 which are successively tightened:

- ≥ 19 to < 37 kW: Stage IIIA (or particle filter) until 2018, particle filter required from 2019
- ≥ 37 to < 56 kW: Stage IIIB (or particle filter) from 2017
- ≥ 56 kW: Stage IIIB (or particle filter) until 6/2017, from 7/2017 Stage IV (or particle filter)

Similar policies on the state level are currently being discussed in Bayern (Bavaria) and Niedersachsen (Lower Saxony). An overview of examples for construction machinery air quality policies on different levels in Germany is summarized in Table 4 below.

Table 4. Examples for construction machinery air quality policies in Germany beyond European legislation.

Level	**Measure**	**Scope**
National	Use of particle filters	Tunnel and underground construction
Federal state	Compliance with latest emission Stage or use of particle filter	Selected municipalities in the State of Baden-Württemberg
Municipal	Compliance with IIIB (IIIA ≥ 19 to < 37 kW) or use of particle filter	Berlin, Bremen
Company/project	Use of latest emission Stage or use of particle filter	Tenders for urban construction

Sweden

Emission regulations

Swedish emission limits follow the EU emission requirements and was last updated in 2012 (SFS 1998:1709).

There are currently no legal policy instruments in Sweden besides the EU regulations aimed at NRMM when it comes to environmental requirements, but only mutually agreed public procurement requirements on machinery used in construction. Work on potential policy instruments for the non-road sector has been carried out during the past years and the conclusion of this work is described below.

Public procurement

The Swedish Transport Administration and the three largest cities are cooperating on a common set of requirements for construction tenders. For construction work started 2012 or later in the main cities, diesel fueled non-railway NRMM covered by EU emission standards must comply with at least Stage III A (Swedish Transport Administration, 2012b). NRMM not covered by the EU standards must not be older than 6 years. Construction work commissioned outside the three cities by the Swedish transport Administration is also contracted with less strict emission requirements. Requirements in the procurement currently focus on machinery and not fuel used. A possible set of requirements aimed at fuels – with a minimum share of renewables – has been developed in a pilot project but not yet used.

General policy instruments

Sweden has two types of tax of fuel: carbon tax and energy tax. Fuels sold for usage in combustion engines are taxed, but with a number of exemptions based on fuel and usage. Biofuels that complies with the EU sustainability criteria are fully exempted of carbon tax and partly relieved of energy tax.

Fuel bought for usage in mining, forestry or agriculture is eligible for tax deductions of either carbon or energy tax. In 2017, the carbon tax on the most common diesel fuel (MK1) is 2.49 SEK/litre and the energy tax is 3.24 SEK/litre totalling 5.73 SEK/litre. NRMM in agriculture, aquaculture and forestry have total deduction of taxes of 1.7 SEK/litre (equalling 29.7 % in 2017) and NRMM in mining have a carbon tax reduction of 40 % and an energy tax deduction of 89 % (equalling 3.88 SEK/litre in 2017).
Over the years 2010- 2015, the reduction of carbon and energy tax was decreased on a yearly basis in order to increase incentives for fuel efficiency in agriculture and forestry. In 2016, tax deduction increased due to market competitiveness.

As of March 17th 2017, a proposal for a climate protection quota similar to that of Germany was presented by the government but is not yet decided. The quota is aimed at fuel suppliers who will have to reduce their CO_2-emissions by a certain percentage. The quota targets diesel fuel in general and not NRMM specifically, but will affect NRMM since diesel fuels sold are the same for NRMM and road vehicles. However, there is still a possibility that diesel blended with renewable components will be used in road vehicles and not to a large extent in NRMMs. There are currently unblended volumes of diesel sold outside publicly available filling stations and it is assumed that a majority of these volumes are used for NRMM although the liters of diesel are not traceable (WSP, 2017).

Future policy instruments

There have been a couple of initiatives on how to include NRMM in the target of a fossil free society in 2050. The main strategies are concluded to be electrification and hybridization, fuel taxation and further work on EU-regulations and development on test methods for energy efficiency and carbon CO_2 (Swedish Environmental Protection Agency, 2012). Many of the investigated policy instrument relies on the possibility to measure fuel consumption and CO_2 emissions in a standardized, and preferably EU harmonized, way.

A recent report for the Swedish Energy Agency suggests that the construction and industrial sectors are better suited for policies than other sectors (WSP, 2017). For construction, this is due to the relative stationarity (compared to forestry or agriculture machinery) and the large proportion of work commissioned by the public sector. It is also argued that alternative technologies for construction equipment are closer to a market introduction than for other types of NRMM. In industrial use it is also judged to be suited for policy instruments due to stationarity, high degree of usage and fewer models in use than e.g. agriculture.

Forestry NRMMs have no options for alternative technologies today, but research on alternatives technologies is judged to have potential. Sweden has a larger proportion of the market for forestry NRMM, than for e.g. construction machinery. Policy instruments considered are fuel taxation, emission zones, subsidies for retrofitting or replacement of old machinery with new and research funding. No policies are decided or suggested.

The reduction of fuel tax for mining, agriculture and forestry is discussed to be removed or at least reduced. Increased energy tax is believed to biofuels since they are relieved from carbon tax.

In addition to the existing public procurement requirements, carbon dioxide requirements are discussed to be added. At the moment, there is no test procedure or emission limit for CO_2 regarding NRMM, however CO_2-emissions has to be measured. It is suggested that it is easier to put requirements of renewable fuels than on fuel consumption and energy efficiency due to the lack of standardized measurement methods. The development of telematics in NRMM is also identified to be of use and makes it possible for the public sector to require that contractors should declare fuel efficiency or fuel usage for a contract.

encourage work on energy efficiency, since fuel economy becomes more important. Increased carbon tax should increase the incentives to choose
In relation to a current proposal for Low Emission Zones for light vehicles, the possibility to also include NRMMs has been discussed. However, it was decided to leave them out due that all machinery is not included in the national vehicle register and it is difficult to follow-up enforcement. One possibility could be to start with including the NRMMs that also drive on public roads, since they are already in the national register and it is easier to enforce regulations when centrally stored information is readily available.

Electrical and hybrid road vehicles are currently classified into emission classes “electrical” and “hybrid”, whilst NRMMs have no corresponding emission classes. The possibility to introduce emission classes for electrified NRMMs is considered to simplify emission zones, tax relief or other regulation for non-road vehicles. Work is needed to define emission classes to ensure that they are fair. A challenge could be to avoid classification of a NRMM as “hybrid” when only a minor part of operations are powered by electricity.

A subsidy for purchasing new NRMM powered by electricity or hybridization has also been investigated. The possibility to introduce a subsidy is deemed as limited, due to EU state aid regulations. There is also a risk of subsidizing the purchase of NRMM in Sweden that is later exported to other countries.

A three year trial (Swedish Board of Agricultures, 2015) concluded that retrofitting subsidies for diesel-to-gas is not recommended. Although the trials were technically successful, the technology is not considered mature enough. A subsidy to a solution that is not commercially available is not feasible.

Switzerland

Air quality and soot in particular is the main concern for Swiss non-road machinery. As in many other European countries, the Swiss population is exposed to particulate matters and nitrogen oxides from vehicles and machinery. Local geography makes certain areas particularly sensitive to air pollution and the exposure tends to increase with the population density of a city. With this in mind, steps have been taken to reduce the harmful effects of soot emitted from NRMM.

Road vehicles are regulated by the same standards as EU road vehicles, which means that NRMM which are authorized to be used on public roads such as tractors are also subject to EU regulation. For other NRMM, rules are set sector by sector. The first sector to be targeted was underground construction, where measurements in the 1990s showed how tunnel workplace environment was harmful due to high levels of soot. Introducing DPFs successfully lowered the soot emissions.

Construction

The first rules concerning construction equipment were introduced in 2002 where machinery at a power > 18 kW were required to have a DPF. Previous attempts with DPFs for tunnel construction equipment had shown that emission levels went down considerably, resulting in improved work environment for tunnel workers. In connection with tunnel test, extensive testing of DPFs showed that not all filters met the requirements. A list of approved filters was established.

The 2002 rules had room for interpretations and were not enforced equally between cantons, and therefore work started to develop uniform rules. Regulations were revised in 2009 and since then the rules apply for all Swiss construction sites. At the same time, an official standard to test particle filter system has been established (Swiss standard SN277206). In addition to the EU emission standards (97/68/EC), the number of particles (PN) is limited to $1\text{x}10^{12}$/kWh for all NRMM used on construction sites. Alternatively, the PN-limit is deemed to be met if a certified DPF is retrofitted. These requirements came into force for construction machinery with a power > 37 kW and year of construction 2000 from 2010. Older machinery with a power > 37 kW and year of construction before 2000 was exempted until May 2015, whereas smaller machinery between 18 – 37 kW manufactured from 2010 had to comply with the rules by 2010. Machinery with < 18 kW is still unregulated.

Snow groomers

Switzerland has a great number of winter sport resorts and it is estimated that about 1 400 snow groomers operates throughout the Swiss Alps. Since snow groomers operate in public space, they are required to be road legal and must thus comply with European NRMM regulation (97/68/EC).. There are no national requirements, but a few cantons have additional regulations and include emissions from snow groomers in their air pollution control programs, meaning that they are required to be equipped with DPF.

Inland waterways and Railways

Since 2007, the Ordinance on Exhaust Emissions from Ship Engines specifies a particle filter requirement for all diesel engines in new passenger and cargo ships in commercial operation. The requirement also applies to existing vessels in case of an engine replacement, as long as it can be considered technically and financially feasible.

Similarly, the provisions of the Railway Ordinance specify that all newly purchased diesel locomotives must be equipped with a particle filter or with another equivalent system to reduce emissions. As with inland waterways, the requirement also applies to replacement engines in existing locomotives.

Switzerland is currently reviewing the possibility to replace all existing emission requirements for NRMM by EU regulation 2016/1628 (stage V).

United Kingdom/London

London introduced a Low Emission Zone (LEZ) for NRMM in 2015. Focus is set on emissions of NO_X and PM to improve air quality (King's College, 2015). NRMM used in major construction sites in greater London will have to meet Stage III A and NRMM used in a smaller, more central area will have to meet Stage III B. In 2020, the requirements will sharpen and Greater London will require Stage III B and inner London Stage IV.

Developers are required to keep track of the NRMM used on-site with a net power between 37 and 560 kW and register them in a common online-register. Machinery can be registered and tracked by various identification numbers. If the NRMM is approved for road use, license plate number can be used, otherwise engine plates are used. If a NRMM intended for use does not meet the requirements, the developer will have to comply with the standards by retrofitting, change of engine or file an application for an exemption. Retrofitting with e.g. DPF should be made with devices from a list of products provided by the Energy Saving Trust NRMM.

Finland

In Finland, reduction goals of energy consumption and CO_2 emissions in the transport sector is mentioned briefly in the document *Government report on the National Energy and Climate Strategy for 2030* (2017). Greenhouse gas emissions from machinery have remained more or less unchanged in recent years. The current EU regulation on machinery engines concerns conventional air pollution rather than energy efficiency or CO_2 emissions. (Ministry of Economic Affairs and Employment of Finland, 2017).

For the part of light fuel oil used in machinery, a 10% blending obligation with bioliquids will be introduced. Extending regulation to energy efficiency and CO_2 emissions would direct the product development of EU manufacturers in the machinery sector and guarantee a declining trend in emissions as the machinery fleet is replaced. The deployment of innovative technical solutions related to energy consumption could thus be promoted. From 2017, the type approvals will also enable the use of biogas in tractor engines, which will contribute to cuts in emissions.
(Ministry of Economic Affairs and Employment of Finland, 2017).

Conclusion

Policy options for affecting NRMM can basically be divided into administrative (legal), economical, information dissemination and research/ demonstration. The policy instruments can be general, including but not targeting NRMM, or policy instruments that specifically address NRMM. Policy instruments can target climate and energy aspects or air pollution (or both). According to this assessment, following policy instruments are available;

Carbon dioxide/ climate/ energy efficiency

- *Regulation of CO_2 emissions*,

Comment: So far no EU regulation of CO_2 is on the way.

- *Refund of energy tax on use of biofuels.*

  Comment: Available in Germany (Bavaria) for new acquisitions and retrofitting of tractors and other mobile machines.

- *Fuels taxation to increase incentive to energy efficiency (focus on energy or carbon). Biofuels can be exempted of carbon tax and/or relieved of energy tax.*

  Comment: Tax target diesel fuels in general and not NRMM specifically, will still affect NRMM since diesel fuels sold are the same for NRMM and road vehicles. However, there is still a possibility that diesel blended with renewable components will be used in road vehicles and not to a large extent in NRMMs.

- *Requirements of a renewable minimum share in fuel.*

  Comment: In Sweden, requirements in the public procurement currently focus on machinery and not fuel used. Has been developed in a pilot project but not yet used.

- *Demonstration projects for use of biofuels.*

  Comment: A pilot and demonstration project for the use of domestic vegetable oils in agricultural machinery is promoted in Germany (Nordrhein-Westfalen). The aim is the demonstration of the full suitability of the tractors and significant reductions in greenhouse gases and at the same time increased contributions to domestic protein supply.

- *Enable type approvals tractor engines using biogas.*

Air pollution

- *Retrofitting of machinery stock with legal measures.*

  Comment: New construction machines (>18 kW) in Germany had to comply with a strict particle number limit at all construction sites, which makes the use of diesel particle filters (DPF) obligatory. In Switzerland, there are legal requirements to use DPFs for all construction machinery > 37 kW .
- *Introduction of Low Emission Zone (LEZ)*

  Comment: Applied in London, UK. NRMM used in major construction sites in a certain area will have to meet a certain emission standard. Developers are required to keep track of the NRMM used on-site and register them in a common online-register.
- *Apply local requirements for use of construction machinery*

  Comment: This is applied in some urban municipalities in Germany.
- *Require compliance with certain emissions standards for construction machinery used within municipal tenders (public procurement).*

  Comment: This method is applied in Germany in several urban municipalities. In Sweden, requirements are only applied to areas within the municipalities of the three largest cities or commissioned by the Swedish Transport Administration.
- *Use working environment requirements to spread technology*

  Comment: In Germany until 2013 only machinery in tunnel and underground construction had to be equipped with particle filters, due to work environment requirements. This requirement indirectly had led to that individual players increasingly have been using "clean" machines on construction sites.

The main strategies for future policy instruments are concluded to;

1. Fuel taxation
2. Develop methods of how to measure fuel consumption and CO_2 emissions in a standardized way
3. Introduce subsidies for retrofitting of old machines
4. Replacement of old machinery with new and research funding
5. Introduce emission classes for electrified NRMMs is considered to simplify emission zones, tax relief or other regulation
6. Introduce subsidies for purchasing new NRMM powered by electricity or hybridization. (The possibility is deemed as limited due to EU state aid regulations. There is also a risk that they later are exported.)

A problem to regulated NRMM is the lack of national vehicle registers. However, if the NRMM is approved for road use they are already in the national register and easier to enforce regulations.

Construction and industrial sectors are believed to be better suited for policies than other sectors. For construction, this is due to the relative stationarity and the large proportion of work commissioned by the public sector. Alternative technologies for construction equipment are also closer to a market introduction than for other types. In industrial use it is also judged to be suited for policy instruments due to stationarity, high degree of usage and relativity fewer models in use.

Machinery testing

Summary of national contributions

The measurement part of the Annex 50 project has been carried out in collaboration with institutions in different countries, and measurement data has been delivered from four countries: Sweden, Finland, Canada and Switzerland. The datasets are however very different in the sense of methodologies and other aspects, which makes a direct comparison inappropriate.

However, despite all the unbalances, it was decided to present the rough picture of NRMMs performance with respect to NO_X- emissions. Emission factors (g/kWh) from all the four countries assembled are shown in the diagram below (Figure 13), as a function of engine power. The colors differentiate the emission standards (Stages) as well as the old machinery retrofitted for NO_X-reduction.

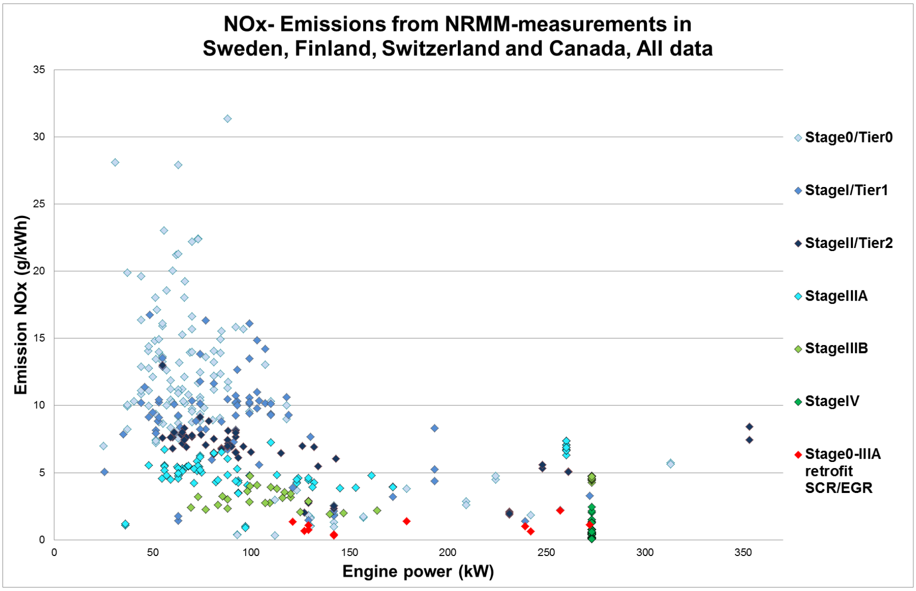


Figure 13. Illustration of NO_X- emission factors when assembling all collected measurement data from four countries. The data is divided by emission standards (colors) and old machinery retrofitted for NO_X-reduction.

Switzerland
Influence of the Aging of Tractor Engines on Performance

Introduction

Switzerland's contribution of measurement data to the Annex 50 was based on extensive emission measurements on tractors. The following text is a summary of a power point document on the measurements that was provided by the Federal Department of Economic Affairs and that has been presented at Internationale Tagung Landtechnik, 27-28 October 2010 (Landis, 2010). The measurement data itself was delivered in an excel sheet, that also included newer measurements (until 2014) on newer machinery (until manufactured 2014). Unfortunately the available information on about how these measurements were performed is scanty.

The purposes of the project were:

- examine how the emissions changed during a period of 14 years (1994-2008).
- evaluate how many hours an engine must run to give optimum results during a measurement (ageing)
- how alternative biofuels affect the emissions (ethanol, RME and rapeseed oil).

Tested machinery

The tested machinery constitutes a data set with more than 200 different agriculture tractors, and spans over about 20 years. In order to analyze how many hours an engine must run to give optimum results, there was randomized selection of 20 machines for the years 1994 – 2002.

Different manufacturers were John Deere, Valtra, New Holland, Deutz-Fahr. Same, Fendt, Steyr. The tractors had different engine types, like 3, 4 or 6 cylinders. Engines capacities were about 3000- 7500 cm^3.

Fuel used in the measurements was conventional diesel. Sulphur content of fuel was:

1. 1st measurement: 300 – 1000 ppm
2. 2nd measurement: < 10 ppm

The general condition of the vehicles show clearly visible signs of usage, the maintenance was very varied.

Measurement method

Measurement of the tractors was performed with identical measuring technique; Exhaust analyzer, Pierburg AMA 2000. The test cycle was in accordance with ISO 8178-4, C1 (NRSC). Measuring points were redefined for each test. The emission parameters measured were HC, NOx and CO.

The majority of the tractors were tested twice. The 20 machines that were selected for aging analysis were tested with a time interval (operation hours) of about 2000 h up to 14000 h. Only four machines were tested for different fuels, and the second tests were performed the day after.

Data evaluation

For emission modeling, deterioration factors were needed. The emission calculations are based on the equation below:

$$Em = N * H * P * l * e * CF_1 * CF_2 * CF_3$$

Em: Emission per machine type [g, resp. t/a]
N: Number of units [-]
H: Working hours [h/a]
P: Mean power [kW]
l: Load factor [-]
e: Emission factor [g/kWh]
CF_1: Load correction [-]
CF_2: Dynamic factor [-]
CF_3: Deterioration factor [-]

Test result

In case of the 20 machines for special testing, specific fuel consumption was roughly the same. There was one vehicle with somewhat better consumption figures. No influence of operating hours detectable at first measurement was observed. For the tests regarding alternative fuels (only four tests), no conclusion could be drawn.

Calculated NO_X-emission factors for all the tractors in the study, and the special 20 tractors for ageing testing marked in red, are shown in the diagram below, Figure 14. The tractors had various emissions standards, which are not shown in the diagram.

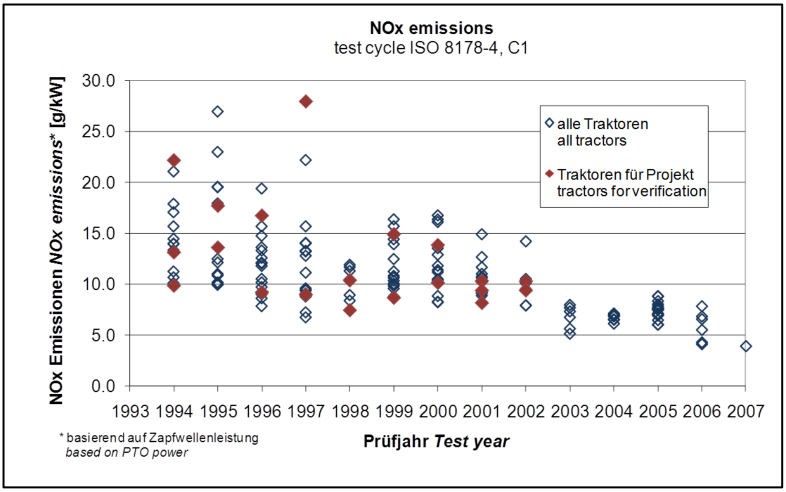


Figure 14. NO_X- emission factors (g/kWh) of all tested tractors, and the 20 tractors tested for effect of ageing marked in red, Landis (2010).

When analyzing the relative change (%) because of ageing, there were no consistent influence of operating hours observed, neither for NO_X, HC or CO, see Figures 15-17. Emission factors in absolute numbers are also presented in the diagrams for the 20 tractors.

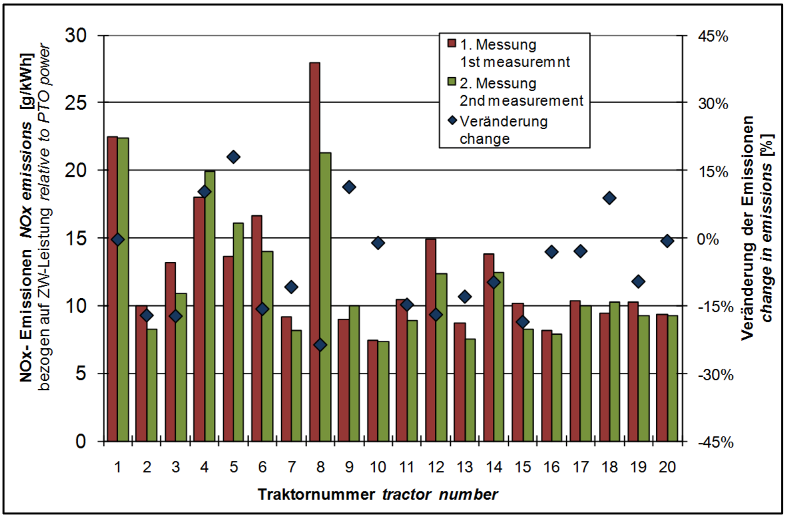


Figure 15. NOx-emission factors (g/kWh) for the 20 tractors analyzed for ageing, and their relative change (%) of ageing (blue dots). Landis (2010)

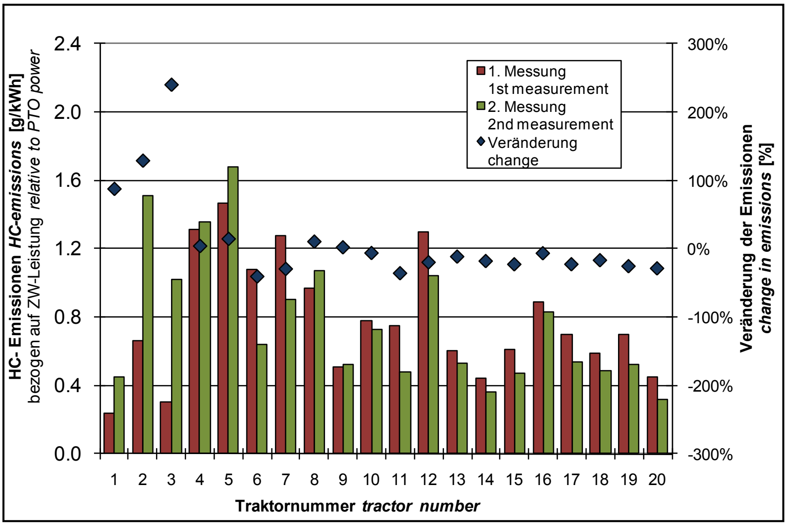


Figure 16. HC-emission factors (g/kWh) for the 20 tractors analyzed for ageing, and their relative change (%) of ageing (blue dots), Landis (2010).

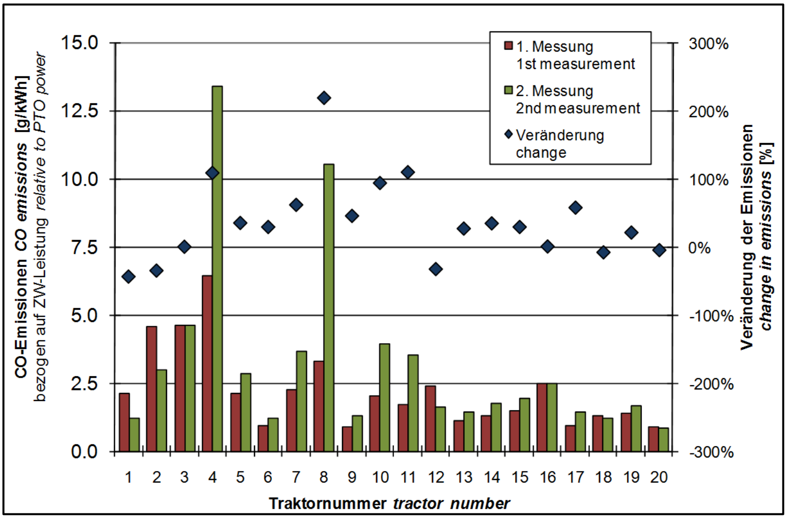


Figure 17. CO-emission factors (g/kWh) for the 20 tractors analyzed for ageing, and their relative change (%) of ageing (blue dots), Landis (2010).

New engines for NRMM in Switzerland must meet the current European emission standards for all regulated pollutants. In addition, Switzerland adopted emission standards for NRMM used in construction that are more stringent than the European requirements. In this context it was chosen to present the Swiss measurement data in relation the EU emission standards.

The overall performance of the NO_X-emissions from Swiss tractors of various emission standards is shown in the Figure 18, below. Emissions are expressed in g/h as a function of engine power (kW), divided by emission standard. The emission limits (Stage 0-IIIB) are represented as solid lines, Stage IIIA has no line since the standard is expressed as NO_X + HC. The picture is indicative and should be interpreted with caution.

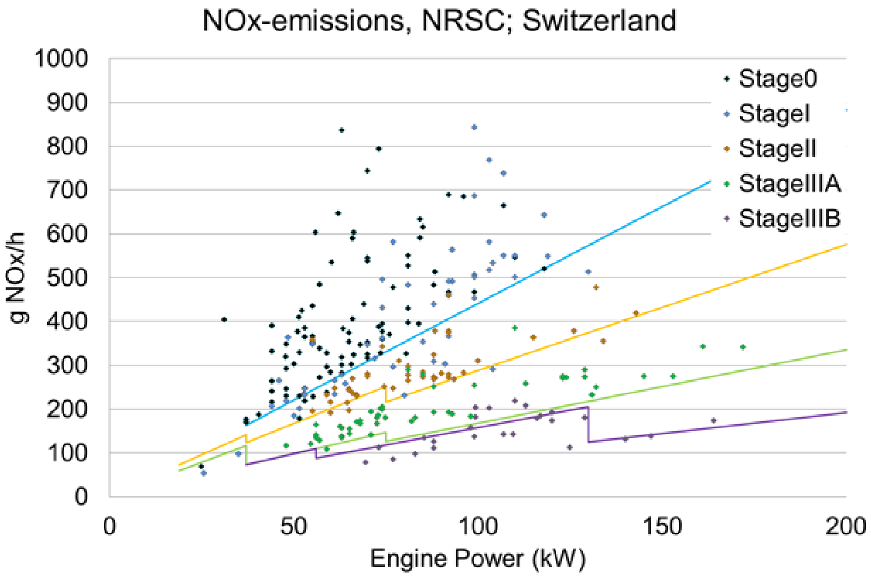


Figure 18. NOX–emissions expressed in g/h as a function of engine power, divided by emission standard (identified by color). The solid lines represent the emission standards. Dots below the solid lines (with the same color) represent legal compliance, dots above the lines non-compliance. Stage IIIA has no line since the standard is expressed as NOX + HC. The figure should be considered indicative.

Conclusion

The successive reduction of the emission factors (NO_X) follows the different emission standards (and limits) in a full reasonable way (Figure 18).

Surprisingly, the majority of performance figures were similar of the first and second measurements, ageing seems to have no effect on the emissions. Some individual tractors had significantly higher emissions.

The emission factors for NO_X are in general slightly higher than the emission limits, though it is important to interpret the result with caution since there are several uncertainties in the calculation methodology.

Anyhow, the general picture of Swiss tractors with respect to NO_X-performance is that there is a clear successive decrease of the absolute emissions over the time period. The same patterns appear for HC and CO (not shown in diagrams).

Canada

Emissions from non-road machinery in their OEM configuration and with retrofit

Introduction

The Emissions Research and Measurement Section (ERMS) of Environment and Climate Change Canada (ECCC) have been involved with a number of studies measuring diesel exhaust emissions from a variety of NRMM. The objectives of these test programs were varied and included quantifying emissions from non-road sources in their OEM (original equipment manufacturer) configuration and with the use of different retrofit emissions reduction technologies.

Tested machinery

All together 34 different units were tested which covered a variety of vehicles and equipment in five different categories, these were:

- 4 bulldozers
- 6 dump trucks
- 9 excavators
- 9 loaders
- 6 units of miscellaneous equipment

The machines are of model year 1973 to 2005 (Tier 0, 1 and 2 engines) and, ranged in engine power from 63 - 522 kW. It should be noted that this represents only older technology machinery and this testing was conducted in the period between 1998 and 2007. For the purposes of the project it was assumed that the equipment were near the end of their useful life hence the worst case for representing the deterioration portion of the emission factor determination. In reality, since most of the test projects involved an assessment of the performance of retrofit emission control systems, the equipment was well maintained.

In some cases multiple units were assessed and in others different fuels were compared using the same equipment, as indicated in the Table 5 below:

Table 5. Specifications of tested non-road diesel machinery, ERMS (2017).

Equipment Type	Machinery type	Make / Model	Power (kW)	Year of Manufacture	Fuel(s) Used
Caterpillar D6H	Bulldozers	Caterpillar	123	1993	LSD
Caterpillar D7R	Bulldozers	Caterpillar	172	2001	LSD
Komatsu D155-Ax-5B	Bulldozers	Komatsu SDA6-D140E	248	2004	ULSD
Tracked Dozer	Bulldozers	Cummins TD-25G	313	1985	LSD
Ford LTS-9000	Dump truck	Cummins L10	209	1993	LSD
International 4700 (2 units)	Dump truck	International T444E	130	1995	LSD
International 60	Dump truck	CAT International 2574 6X4	242	1993	ULSD
Volvo DHD64B	Dump truck	Volvo VED12B	257	2000	ULSD
International	Dump truck	International DT466	157	1988	LSD
Gradall G3WD	Excavator	Cummins 6BTA	129	1992	ULSD
Gradall G3WD	Excavator	Cummins 6BTA	129	2000	ULSD
Gradall G3WD (3 units)	Excavator	Cummins 6BTA	142	1992	LSD
Gradall XL5200	Excavator	Cummins 6BTA	121	1997	ULSD
Gradall XL5100	Excavator	Cummins 6CTA 8.3T	179	1994	ULSD
Komatsu PC-400 HD	Excavator	Komatsu SAA6D 125E-3	261	2004	ULSD
Komatsu PC-750 L6	Excavator	Komatsu SAA6D 140E-3	353	2004	ULSD
Case 821 Loader	Loader	Cummins 6T 830	142	1998	ULSD
Caterpillar 966G Rubber Tire Loader	Loader	Caterpillar 3176C ATAAC	193	2004	ULSD
Recycle Split Rear Loader	Loader	Detroit Diesel Series 50	231	1997	LSD
Caterpillar 966G Wheeled Loader (2 units)	Loader	Caterpillar 3306	317	2002	ULSD
Backhoe Wheeled Loader	Loader	Caterpillar 3054DIT	63	1994	LSD
Front End Loader – Wheeled	Loader	Volvo TD63KBE	112	1994	LSD
Front End Loader – Wheeled	Loader	Caterpillar 988	239	1973	LSD
Automated Side WX64	Loader	Volvo VE	205	1999	ULSD
Terex TR-70 Quarry Truck	Miscellaneous Equipment	Detroit Diesel 12V 2000	522	2005	ULSD
Smooth Drum Roller	Miscellaneous Equipment	Cummins B 3.9-C	93	1995	ULSD
Ingersoll Rand IR 600 Compressor	Miscellaneous Equipment	John Deere 61RF8TE	127	2005	ULSD
Vacuum Pump WG674	Miscellaneous Equipment	Cummins ISM	272	2000	ULSD
Caterpillar 3306B Genset Generator	Miscellaneous Equipment	Caterpillar 3306B Genset	224	1994	LSD
Tamrock CHA700 Hydraulic Drill	Miscellaneous Equipment	Caterpillar 3506E	129	2004	ULSD

Measurement method

The ERMS/ECCC designed and patented a Dynamic Dilution On/non-road Exhaust Emissions Sampling System (DOES2) in the mid-1990s, and prior to the introduction of the PEMS that are commercially available today.

These field measurements were collected during the normal in-service operation over their representative duty cycle. They were running on commercially available diesel fuels purchased locally.

To collect the raw exhaust a probe is inserted into the exhaust pipe of the engine via an exhaust extension. The air then goes through the dilution pumps and is pushed back into a mass flow meter to measure the flow rate.

The diluted sample is collected at the end of the sample line into sample media. This technique is used in order to determine average weighted emission rates over defined periods of operation. During testing, the vehicle/equipment engine is operated under various speed and load conditions.

For most studies, the analysis from the DOES2 collection has been for the following compounds:

- PM (gravimetric method);
- THC (flame ionization detection);
- NO_X (chemiluninescence);
- CO (non-dispersive infrared detection); and
- CO_2 (non-dispersive infrared detection).

Emission rates were reported in g/min and converted to g/kWh for comparative purposes.

All emissions are from OEM configured machinery operating under normal in-service operations over their representative duty cycle. It should be noted that these in-use equipment were tested in their as received condition and maintenance intervals were not a subject of these studies.

Data evaluation

For each of the non-road units emission rates of CO, HC, NO_X, PM and CO_2 were calculated from emissions collected as g/min to g/kWh. Emission factors were then calculated for each of the non-road units for CO, HC, NO_X, and PM.

Comparative emissions data between the OEM configuration and retrofit emission control or commercially available diesel emissions control technologies is available in some cases. The types of technologies compared include:

- Diesel Oxidation Catalysts (DOC)
- Diesel Particulate Filters (DPF)
- Exhaust Gas Recirculation (EGR)
- Lean NO_X catalysts (LNC)
- Selective Catalytic Reduction (SCR)
- Diesel-Water Emulsion Fuel based strategies.

Result

No discernable pattern of emissions based on equipment type was observed, i.e., emissions were high in some cases and low in others within a given non-road category. In the Figure 19 below, there is a graphical representation of NO_X emission rates (g/kWh) as a function CO_2 emission rates (g/kWh) which shows only a moderate correlation between these two parameters.

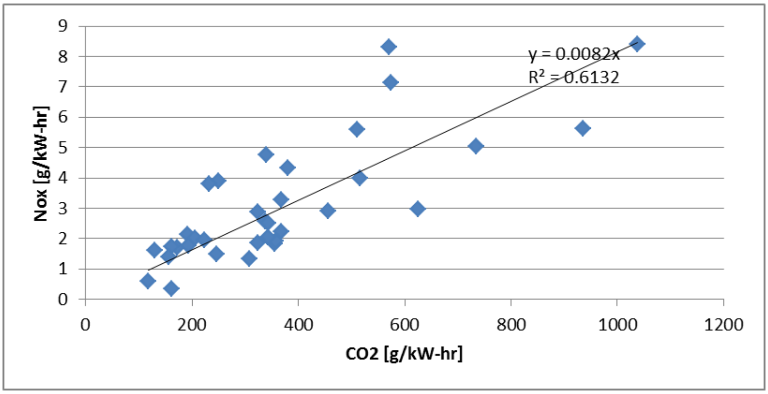


Figure 19. **NOX versus CO2 measured emission rates (g/kWh) from non-road equipment operating under normal in-service operations, ERMS (2017).**

Emission factors for the test equipment were calculated. The emission factors were derived by applying the procedure described in EPA Technical Report NR-009d. The emission factors are based upon zero-hour steady-state emission rates that are then modified by applying transient adjustment factors as well as deterioration factors, while the particulate mass emission rates are also adjusted for variations in fuel sulfur level. The emission factors together with the emissions rates per tested machine are presented in the diagrams below, Figure 20-23 (but without information about control technology).

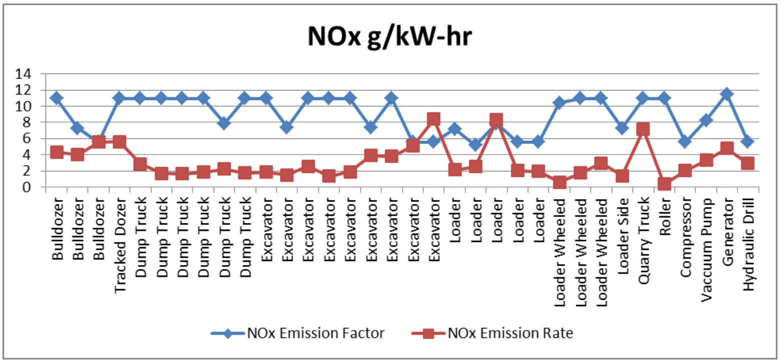


Figure 20. Emissions rates and calculated NOX emission factors (g/kWh), ERMS (2017).

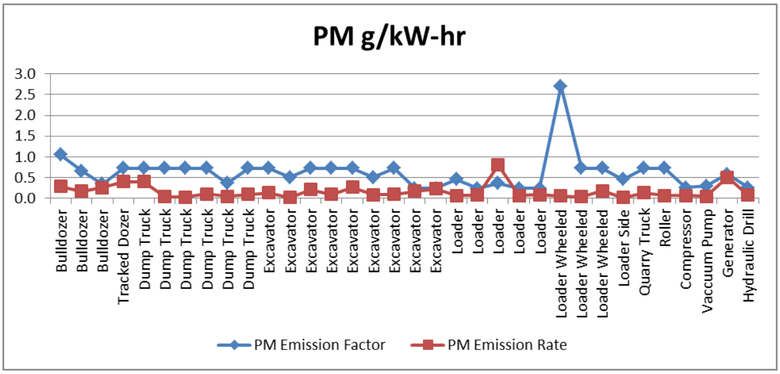


Figure 21. Emissions rates and calculated PM emission factors (g/kWh), ERMS (2017).

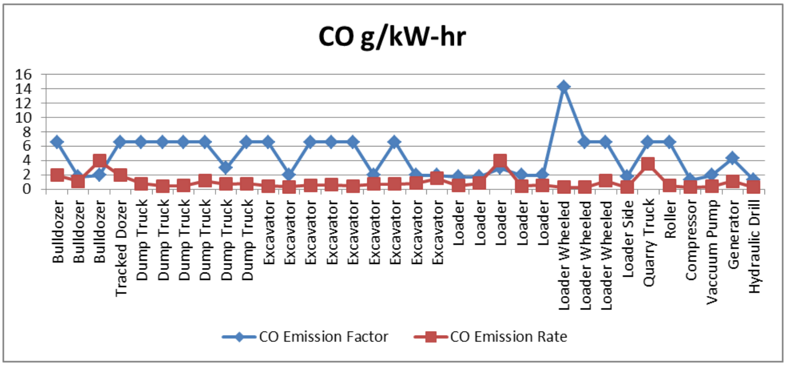


Figure 22. Emissions rates and calculated CO emission factors (g/kWh), ERMS (2017).

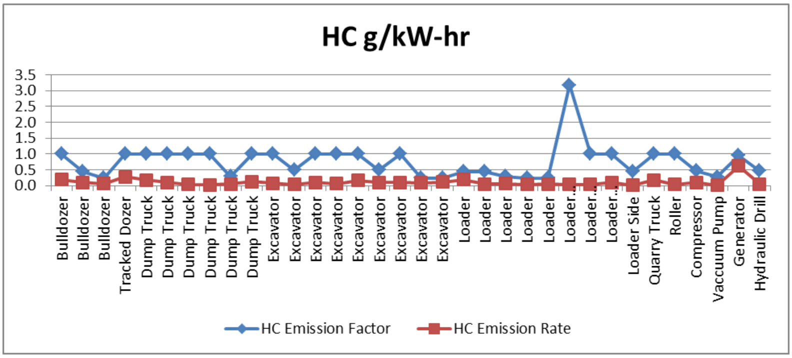


Figure 23. Emissions rates and calculated HC emission factors (g/kWh), ERMS (2017).

For the majority of non-road equipment the emission rates were in the range of or below the calculated emission factors. Of the 34 non-road machinery tested, two of the units showed NO_X emission rates higher than the calculated emission factors with one bulldozer having an emission rate equaling the calculated emission factor.

One of the excavators, the highest powered unit 353 kW, had NO_X emissions exceeding the calculated emission factor. The recycle split rear loader, also exceeded the emission factor. Also, this unit exceeded the calculated emission factors of PM and CO. One bulldozer with the NO_X emission rate equaling the calculated emission factor had a CO emission rate of 3.95g/kWh compared to the calculated emission factor of 1.9g/kWh. The calculated emission factors of PM, CO and HC are highest for the backhoe wheeled loader. This is the resulting combination of the factors used for a 56-75 KW and a Tier 0 engine. This loader was the lowest powered piece of equipment in the test matrix.

The measurement data were also evaluated with respect of the control technologies, and analyzed for the non-road categories separately (bulldozers, dump trucks, excavators, loaders). The result is presented below.

Bulldozers

Figure 24 indicates the emission changes with each of the four bulldozers tested with technologies that have the potential to reduce emissions. Two bulldozers were tested with a diesel-water emulsion blends, one was installed with a DPF and one with a DOC.

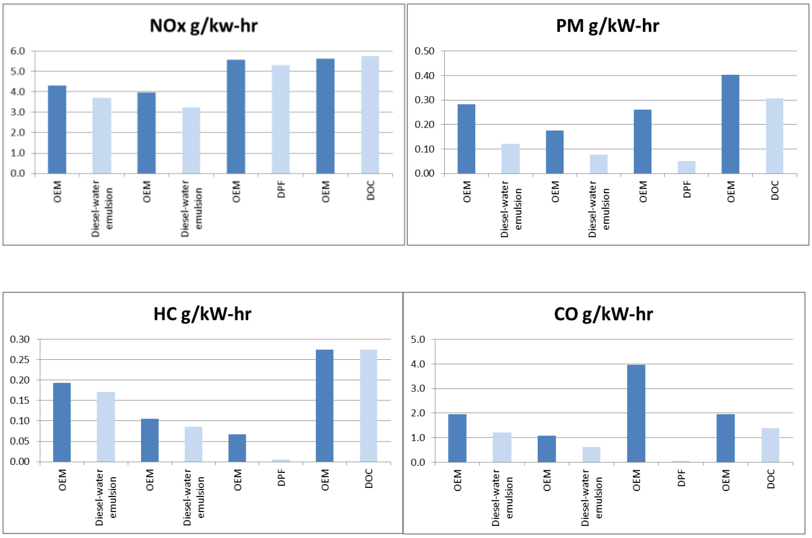
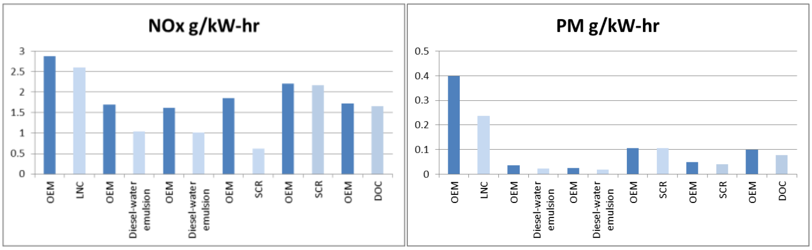


Figure 24. Bulldozer emission rates (g/kWh) with emission controls, ERMS (2017).

Dump Trucks

Each of the dump trucks was tested with an emission control technology (DOC, LNC, SCR) or diesel-water emulsion. See Figure 31 below:



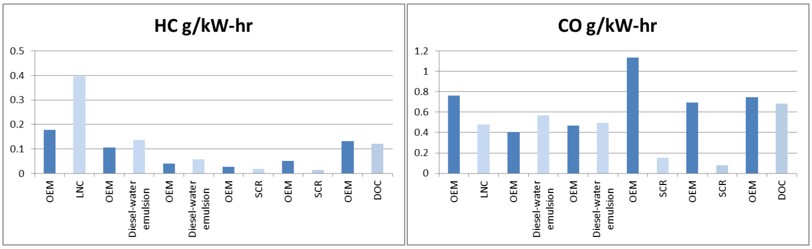


Figure 25. Dump Truck emission rates (g/kWh) with emission controls, ERMS (2017).

Excavators

Each of the nine excavators was equipped with either an SCR and/or DPF technology, or used a fuel emulsion. One excavator was equipped both with SCR and DPF. Five of the excavators were equipped with SCR technologies.

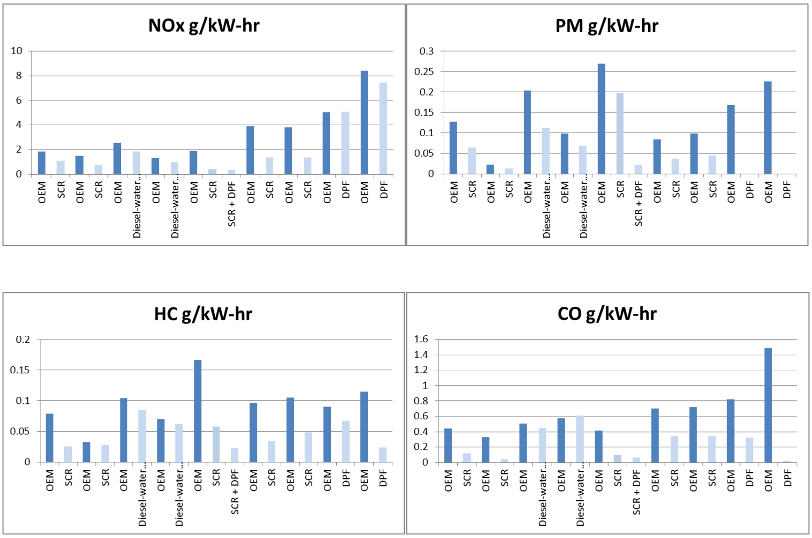


Figure 26. Excavator emission rates (g/kWh) in OEM configuration and with emission control technologies, ERMS (2017).

Loaders

Of the nine loaders tested, six were equipped with DPFs, two with DOC, one with diesel-water emulsion and one used EGR technology.

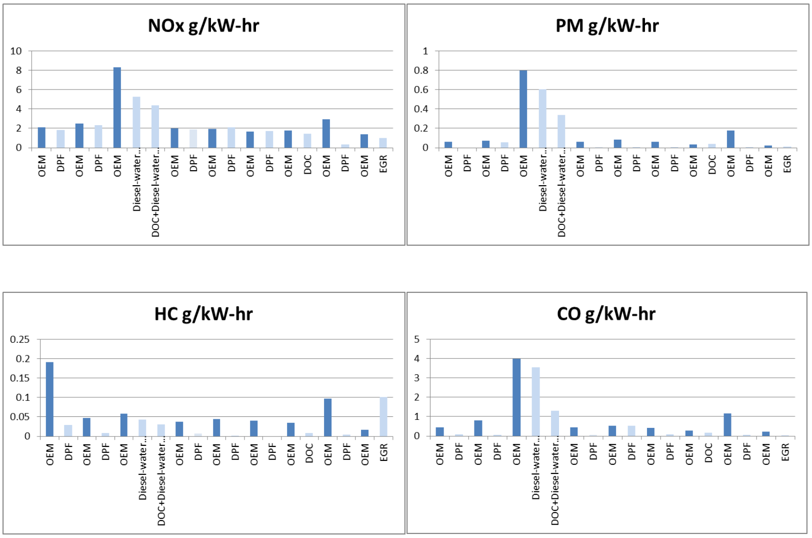


Figure 27. Loader emission rates (g/kW) in OEM configuration and with emission control technologies, ERMS (2017).

Miscellaneous Equipment

Six non-road miscellaneous pieces of equipment were tested with DOC, DPF, SCR and EGR.

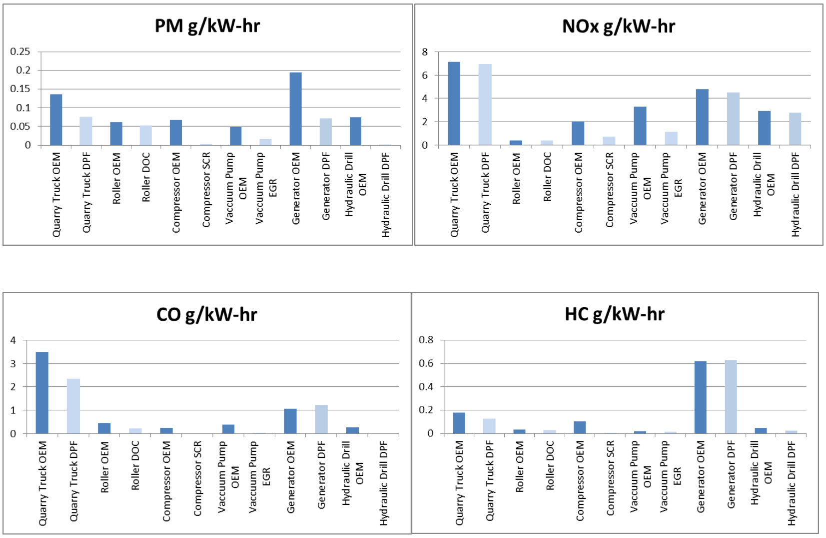


Figure 28. Miscellaneous Equipment emission rates (g/kW) in OEM configuration and with emission control technologies, ERMS (2017).

Conclusion

While the compilation of these one-off field measurements cannot be used to identify trends, the information may be of interest to organizations developing all source baseline emissions inventories predicated on real-world emissions data.

All of these technologies showed the potential to reduce specific emissions from older in-use NRMM. Out of 34 units 13 were equipped with some type of DPF. The DPFs were tested on units that fell into all the non-road categories with the exception of the dump trucks. In all cases the DPF showed reductions in PM, and in the majority of cases these reductions were greater than 90%.

Eight units were equipped with SCR systems in the dump truck and excavators categories. On average the use of SCR technologies reduced NO_X by ca 55% along with in many cases reducing emissions of CO and HC. The excavator that was equipped with both SCR and DPF technology, resulting in a decrease of NO_X of 80%, PM reduction of 90%, CO reduction and HC reduction of 85%.

One dump truck was equipped with a LNC technology which resulted in reductions of NO_X by 10% and reductions in CO (37%) and PM (40%), however HC was increased. One loader was assessed using EGR, and NO_X was reduced by about 25%.

Seven units were tested with the fuel based diesel-water emulsion blend strategy in all categories. The emulsion was effective at reducing NO_X by an average of ca 30% and PM by 40% without for the most part increasing emissions of CO and HC. The diesel-water fuel emulsion was also used in combination with a DOC continued to provide emissions reductions.

DOCs were installed on 5 units; one bulldozer, one dump truck, two loaders and a roller. On all of these types of equipment DOCs were shown to reduce emissions of CO, HC and PM (assumed to be the soluble organic fraction).

Sweden

Introduction

The Swedish contribution consists of two different studies carried out with on-board measurement on wheel loaders;

1. Measurements of three different vehicles and emission standards (Stage IIIA, Stage IIIB and Stage IV)
2. Measurements of a Stage IV wheel loader during several different test cycles representing normal operating conditions.

Both studies were commission by the Swedish Transport Administration and carried out by AVL Motortestcenter AB (AVL) and are entirely presented in Sandström Dahl & Willner (AVL, 2016a) and Sandström Dahl & Willner (AVL, 2016b). The following sections will present a summary of both studies starting with On-board measurements (AVL, 2016a).

On-board emission measurement on three wheel loaders with different emission standards

General

The main purpose of this study was to compare emission performance and fuel consumption of machines of different emission standards. Conformity factors, defined as the ratio of measured emissions to the regulated emission limit, was calculated using five different evaluation methods. The test data was evaluated and presented both as whole tests (no data was excluded), and according to the proposal for in-service conformity for NRMM in the EU.

The effect of the different data exclusions in the proposal in comparison to a whole test was also investigated in the study.

Tested machinery

Three wheel loaders approved in accordance to three different emission standards were tested within the study:

- Stage IIIA (Volvo L220F)
- Stage IIIB (Volvo L220G)
- Stage IV (Volvo L220H)

Volvo L220F

The L220F machine was an older machine with emission standard Stage IIIA. The machine had exceeded its expected lifetime. All tests were performed with commercially available MK1 diesel, with Sulphur content of <10 mg/kg and cetane number of >51. The machine was equipped with an internal EGR.

Volvo L220G

The L220G machine was of emission standard Stage IIIB. All tests were performed with commercially available MK1 diesel, with Sulphur content of <10 mg/kg and cetane number of >51. The machine has a DPF with active regeneration.

Volvo L220H

The L220H machine is of emission standard Stage IV, and was new when the PEMS testing started. All tests were performed with commercially available MK1 diesel, with Sulphur content of <10 mg/kg and cetane number of >51. Equipped with an SCR and a DPF.

Measurement equipment

Portable Emissions Measurement Equipment (PEMS) was used and regulated emissions were measured, those are carbon monoxide (CO), hydrocarbons (THC), nitrogen oxides (NO_X) and particulate mass (PM) as well as fuel consumption (FC) and carbon dioxide (CO_2).

PEMS Equipment, brand and type:

- AVL M.O.V.E GAS PEMS 493
- AVL M.O.V.E PM PEMS 494
- Sensors EFM-HS 5”

The M.O.V.E is developed by AVL for testing of vehicles and equipment under real-world operating conditions. The instrument is an on-board emissions analyzer which enables tailpipe emissions to be measured and recorded simultaneously while the vehicle/machine is in operation. The following measurement subsystems are included in the AVL M.O.V.E GAS PEMS emission analyzer:

- Heated Flame Ionization Detector (HFID) for total hydrocarbon (THC) measurement.
- Non-Dispersive Ultraviolet (NDUV) analyzer for nitric oxide (NO) and nitrogen dioxide (NO_2) measurement.
- Non-Dispersive Infrared (NDIR) analyzer for carbon monoxide (CO) and carbon dioxide (CO_2) measurement.
- Electrochemical sensor for oxygen (O_2) measurement.

The AVL M.O.V.E PM PEMS combines the time resolved photo-acoustic soot measurement principle with a gravimetric PM measurement which operates with a gravimetric filter. The time-resolved particulate (PM) emissions are calculated by weighing the loaded gravimetric filter after the end of the test and, additionally, using the time resolved soot signal and the exhaust mass flow as inputs. The instrument consists of the following main components:

- The Micro Soot Sensor measuring unit (MSS) which is designed for continuous measurement of soot concentrations, and;
- The Gravimetric Filter Module (GFM) which provides total PM using the gravimetric filter method.

The instruments are operated in combination with an electronic vehicle exhaust flow meter, Sensors EFM-HS. The M.O.V.E. instrument uses the flow data together with exhaust component concentrations to calculate instantaneous and total mass emissions.

The PM sampling probe is fitted approximately 50 cm/20” upstream of the exit of the exhaust gas system which is according to EU NRMM directive 97/68/EC (and later amendments). The AVL M.O.V.E SYSTEM GAS PEMS 493 has been verified by TÜV and meets the requirements of the regulation (EU) NO. 582/2011 Annex II and (EU) No. 64/2012, certification no: 2013-06-03- AM-Z.01. The AVL M.O.V.E PEMS system is also approved according the standards of the U.S. Environmental Protection Agency (EPA), 40 CFR Part 1065. AVL PM PEMS 494 has by EPA, 40 CFR Part 1065, been approved as an alternative system.

Test site and method

The test location was a gravel-pit managed by the Swedish construction enterprise Skanska and located near Eskilstuna, Sweden. The measurements were performed during the daily use. The three machines performed similar work during the testing, basically consisting of movement of gravel at the work site. The work performed by the wheel loaders were generally very transient with frequent change of load (full bucket- empty bucket- full bucket etc.), and with very limited idle periods. Two test sequences were performed for each machine.

The actual engine power from one test for each machine showing similar load patterns (%). Tailpipe exhaust temperatures for the different machines show adequate temperatures for proper after treatment system functionality.

Measurement data evaluation

The data evaluation software has been verified by TÜV and meets the requirements of the regulation (EU) NO. 582/2011 Annex II and (EU) No. 64/2012, certification no: 2013-06-03-AM-Z.02.

For each machine two tests were performed and evaluated both as whole test and according to the averaging window principle based on work and CO_2 mass, as proposed for *In-Service Conformity Procedure* for NRMM in EU (EU, 2010). All test results are presented as drift corrected, the whole test has been evaluated.

Test results

The results showed reductions for all regulated components for the machines with the latter emission standards. The most significant reductions could be observed for NO_X and PM. The exhaust aftertreatment on the tested machines has followed the development of tougher emission limits for the latter standards. The Stage IIIB and Stage IV machines were equipped with DPFs, and the PM emissions were reduced extensively. One important comment could be that the Stage IIIA machine had expired its expected lifetime; and the Stage IV machine was new when the PEMS testing started, and there is no study of any ageing effects on the exhaust aftertreatment systems.

The reduction of both NOx and PM emissions from Stage IIIA (L220F) up to Stage IV (L220H) is substantial. For the Stage IIIA machine the PM and soot emissions are high. The emissions have been extensively reduced for the Stage IIIB machine, and even more so for the Stage IV machine. The soot emissions are reduced to the same level for both the Stage IIIB and the Stage IV machines, but the PM emissions have been even further reduced for the Stage IV machine. Both these machines are equipped with DPFs, but the DPF for the Stage IV machine is more advanced. Figure 29 and Figure 30 shows NO_X and PM emissions for all three machines evaluated for the whole tests.

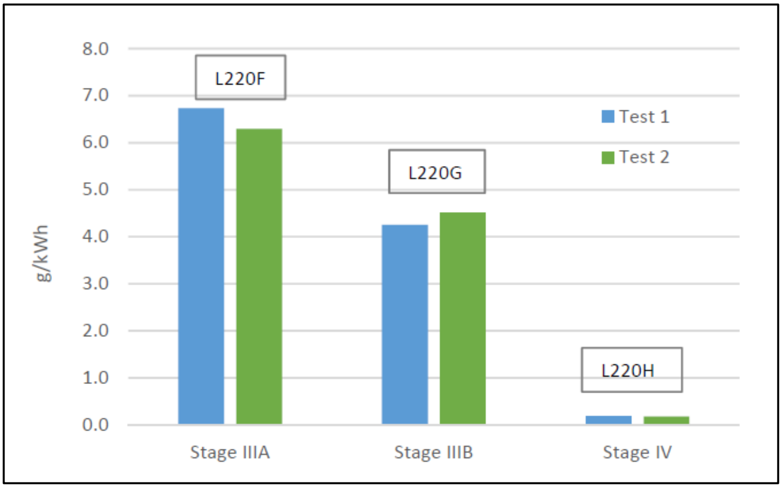


Figure 29. Emissions of NOx (g/kWh) during a whole test, Sandström Dahl and Willner (2016a).

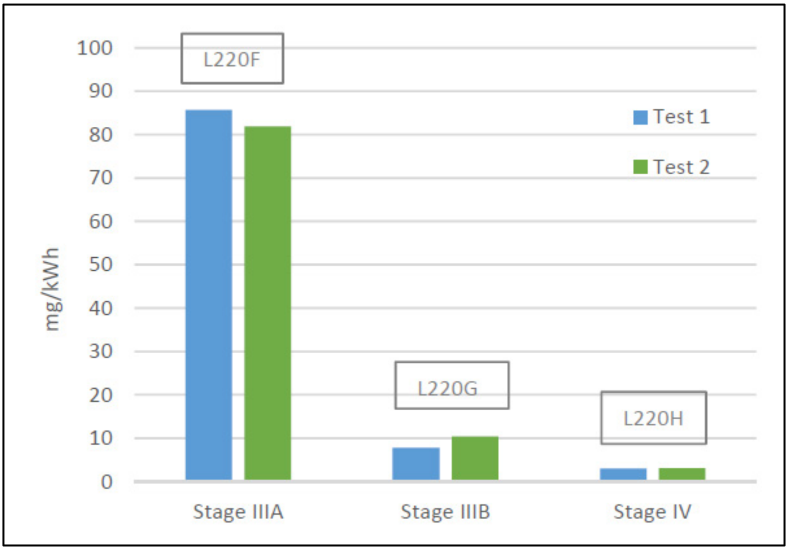


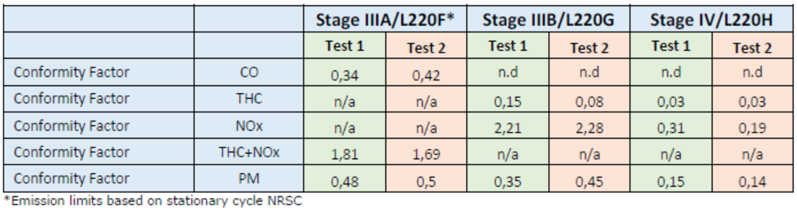
Figure 30. Emissions of PM (g/kWh) during a whole test, Sandström Dahl and Willner (2016a).

The CO_2 emissions have however not been reduced with the latter emission standards. The Stage IIIB machine emitted almost 20% more CO_2 than Stage IIIA, and the Stage IV machine approximately 6% more. CO_2 emissions are not yet regulated.

Conformity factors are not allowed to exceed 2 for NRMM according to the proposal for in-service conformity for NRMM in the EU.

The machines tested in this study are within the acceptable conformity factors calculated from a work-based window in accordance to the proposal for In-Service Conformity for NRMM. The exception is NO_X emissions from the L220G machine (Stage IIIB), see Table 6. If instead using the CO_2-based window method the Conformity Factor for NO_X is below 2 for the L220G. The difference between the work-based and the CO_2-based methods are discussed in Bonnel *et al.* (2011) where it was found that these approaches are nearly equivalent from a technical perspective. One explanation for discrepancies might be that the work/CO_2 mass ratio varies slightly as a function of the engine operating conditions.

Table 6. Conformity factors tested machines, using work-based window, Sandström Dahl and Willner (2016a).



		Stage IIIA/L220F*		Stage IIIB/L220G		Stage IV/L220H	
		Test 1	Test 2	Test 1	Test 2	Test 1	Test 2
Conformity Factor	CO	0,34	0,42	n.d	n.d	n.d	n.d
Conformity Factor	THC	n/a	n/a	0,15	0,08	0,03	0,03
Conformity Factor	NOx	n/a	n/a	2,21	2,28	0,31	0,19
Conformity Factor	THC+NOx	1,81	1,69	n/a	n/a	n/a	n/a
Conformity Factor	PM	0,48	0,5	0,35	0,45	0,15	0,14

*Emission limits based on stationary cycle NRSC

Effect of data exclusion

The effect of the different data exclusions was tested by using five different calculation methods. In Table 7 different evaluation combinations are explained, where evaluation method 1 represents the officially proposed NRMM-method. According to this method, the conformity factor should be calculated by using the 90% cumulative percentile of the respective emission component. Also, a 20% power threshold should be applied, where the average power has to exceed 20% for the work window to be considered as valid.

Table 7. Evaluation combinations, Sandström Dahl and Willner (2016a).

Evaluation method	100 percentile	90 percentile	20% power threshold	0% power threshold	Non working events (yes/no)
1		x	x		yes
2		x	x		no
3	x		x		no
4		x		x	no
5	x			x	no

The effect of the removal of non-working events can be studied by comparing evaluation method 1 and 2. Method 2 and 3 compares the effect of removing the windows with the highest values. The 20% power threshold is not applied in method 4; whereas in method 5 there is neither removal of high values nor removal in regards to the power threshold. It is however important to remember that the effect of removal of non-working events are depending on the driving cycle. For the wheel loaders tested in this project, the machines were tested at high loads with very short periods of idling.

For the L220F machine (Stage IIIA) there are differences depending on the method to evaluate, see Figure 31. The wheel loader was tested during highly transient conditions, with high load and very short periods of idling. The effects of removal of non-working events have no effect on the results, neither when changing the power threshold. The effects of evaluation methods for the L220G machine (Stage IIIB) shows small differences (NO_X) between method 1 and 2 (non-working events removed). The greatest effects could however be observed with the removal of the 90% cumulative percentile, which also reflects the actual levels of exhausts emitted to the atmosphere.

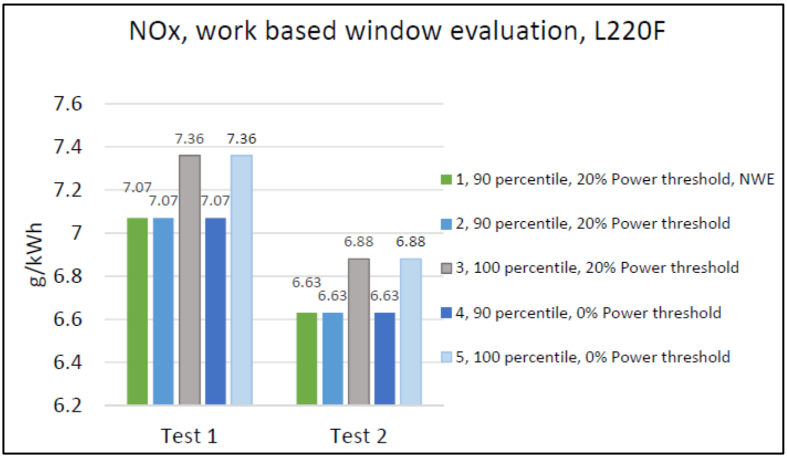


Figure 31. Comparison of NO_X emissions for Stage IIIA/L220F – different evaluation methods, Sandström Dahl and Willner (2016a).

The same pattern could be observed when looking at all three machines, with a significant difference between removal vs inclusion of the windows with the highest values. The differences in % are however much more distinguished the latter the emission Stage – with differences of approximately 3-4% for the L220F (Stage IIIA) up to more than 100% for the L220H (Stage IV) machine.

On-board emission measurement on wheel loader in different test cycles

General

In this study emission validation tests were carried out on one wheel loader (Volvo L220H). The tests were carried out using a number of different test cycles. The purpose of the testing was to investigate how different data exclusion methods in the work based window method proposed for the In-Service Conformity for NRMM in EU, influences the Conformity Factors of machines operating in different typical non-road machine applications (EU, 2010).

Tested machinery

The tested wheel loader was a Volvo L220H machine of emission standard Stage IV. The machine weight was 35.5 tonnes and the engine rated power 273 kW. It used SCR and DPF for exhaust aftertreatment and had operated approximately 1500 hours at the time for the test.

Measurement equipment

PEMS Equipment:

- AVL M.O.V.E GAS PEMS 493
- Sensors EFM-HS 5"

(for more information about the test equipment, see the previous section *On-board emission measurement on three wheel loaders with different emission standards*.)

The instruments are operated in combination with the electronic vehicle exhaust flow meter (EFM-HS). The instrument uses the flow data together with exhaust component concentrations to calculate instantaneous and total mass emissions. The flow meter is available in different sizes depending on power class of the tested machine. The exhaust gas temperature measured and presented in the report is measured in the EFM (tailpipe).

Test site and method

The tests were carried out using a number of different test cycles. Each cycle represented typical driving situations for various NRMM.

The PEMS instrument was installed on the machine and the measurements were performed during the different test cycles. The test cycles were created in order to represent various possible work applications for many different wheel loaders.

Special effort was given to present difficult situations for the exhaust aftertreatment system. Test cycles were created to include constant as well as transient driving with various load conditions, idle-periods of various lengths, “soft” driving with engine braking and soft take-off after idle as well as more “aggressive” driving. The tests were performed in an “oval” test track.

According to the proposal for In-Service Conformity Procedure for NRMM, the minimum work performed during a valid ISC PEMS test, is the Engine Reference work (work performed during a NRTC-cycle) multiplied by five.

The eight different test cycles were:

1. **Oval, empty bucket.** Operated with empty bucket. The test cycle can be described as "soft". Accelerations were performed with as low and constant engine torque as possible followed by coast down/engine braking to a lower speed or stop. 30 min driving with varying speed and engine brake until almost stand still, followed by 3 minutes idle and change of driver, and then 30 min driving again (same as above)

2. **Oval, empty bucket. S**imilar to nr 1. 30 minutes driving with varying speed and engine brake until almost standstill, followed by 3 minutes idle, and then 20-30 min driving, 3 minutes idling again, this was repeated four times, and the cycle ended with 4 minutes light low speed driving follows by slow acceleration and 15 minutes driving with varying speed and engine brake until almost standstill.

3. **Oval, full bucket.** Operated with full bucket. The engine load was varied by aggressive driving followed by coast down/engine braking to a lower speed where the temperature in the after treatment system was allowed to drop. Short periods of idle through the whole test.

4. **Oval, full bucket.** Same as nr 3, but switch between driving and idling were repeated four times (2 min- 20 min).

5. **Hill cycle.** The machine was operated transiently with heavy load, full power and torque, going up and down a hill. When the temperature in the after treatment system was stable, the machine stopped for various periods of idle followed by slow take off. First 20 min up/down followed by 5 min idling, then 15min up/down and 6-30 minutes idling repeated four times.

6. **Short transport.** The machine was used to move gravel from one pile to another. The test cycle can be described as more aggressive with many “hard” accelerations. Three different transport distances were tested. A bucket full with gravel adds approximately 11-12 tons to the machine. Short transport distance (20 m), 15-20 min idling and 4-12 min idling between, repeated four times.

7. **Medium transport.** Medium (115m) transport distance. 20 min driving, and 8-12 min idling between repeated three times.

8. **Long transport.** Medium (215m) transport distance. 20 min driving, and 4-12 min idling between repeated three times. The part of the test where DPF regeneration occurs is excluded from the calculations and are instead calculated separately.

9. Regeneration.

Measurement data evaluation

According to the proposal for In-Service testing for NRMM, there are data exclusions which should be applied to the test data, where the data are analyzed through moving average windows based on work or CO_2-mass. Some of these excluded data were certain criteria regarding ambient pressure, ambient temperature and engine coolant temperature are not met. These exclusions are applied to all calculations of conformity factors. Other exclusions marks windows where the average power is below 20% as invalid and deletes windows with the 10% highest delta-values for the respective emission component.

Yet another exclusion have primarily been introduced to handle long periods of idling: periods of idle longer than 2 minutes are classified as a "non-working-event" (except the first 2 minutes). A non-working event can be either long (>10 minutes) or short (< 10 minutes).

The test results were calculated both as whole tests and according to the proposal for In-Service conformity for NRMM in EU. Each test has been evaluated with and without the non-working event exclusion.

The Conformity Factors for the machine are calculated based on the legislated emission limits. The emission standard is based on the transient test cycle NRTC.

Test results

The emissions of CO and THC are negligible and hence this result section focuses on NO_X emissions. Figure 32 presents the NO_X emissions in g/kWh in the different test cycles. The seen differences do not so much depend on the differences of the test cycles. As long as the machine is actively operating and the exhaust after treatment system warmed up, the emissions are at a relatively constant and low level. What is reflected in the results is in most cases various periods of idle.

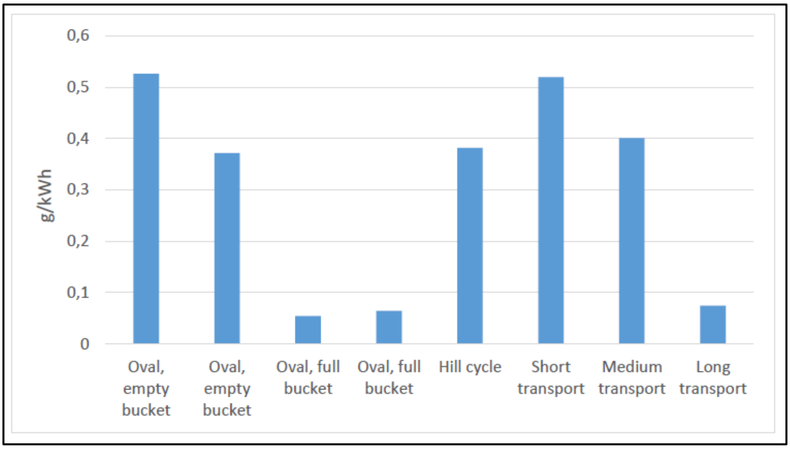


Figure 32. Emissions of NOx (g/kWh) from the whole test, Sandström Dahl, C., Willner, K. (2015b).

In Table 8 the Conformity Factors from work-based windows, calculated according to the proposed In-Service testing Procedure, are presented together to enable comparison of the cycles. The machine tested in this study is within the acceptable Conformity Factors calculated from a work-based window in accordance to the proposal for In-Service Conformity for NRMM.

Figure 33 shows the discrepancies regarding Conformity Factors between the different cycles.

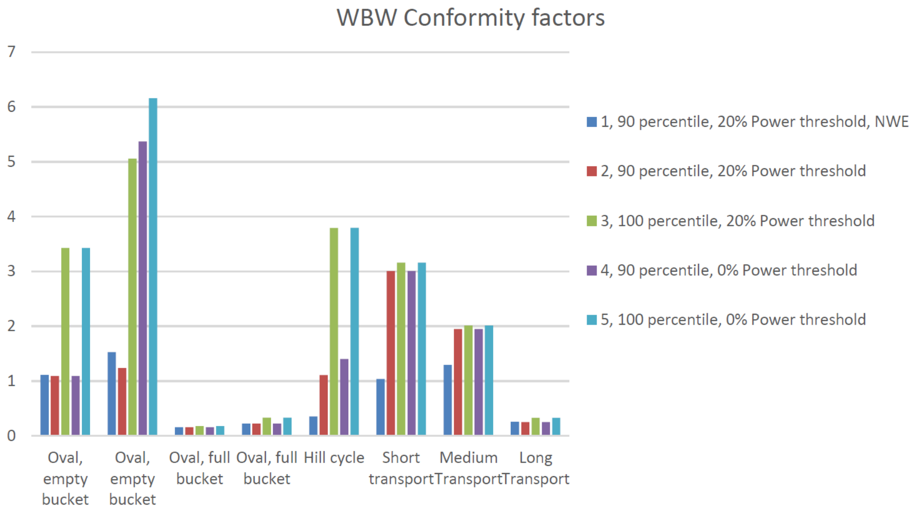


Figure 33. WBW Conformity Factors for NO_X, all tests, all evaluation methods, Sandström Dahl, C., Willner, K. (2015b).

Idle periods (<10 min or 10- 30m min) have the greatest impact on the Conformity Factors when using the non-working event exclusion, whereas the majority of the increased NO_X-emissions from idle periods slightly longer than 10 minutes are eliminated. It seems however that the 10 minutes as duration limit for short versus long non-working events is a suitable choice in order to determine conformity towards the test cycle.

Table 8. Summary of Conformity Factors for the machine in the different test cycles, Sandström Dahl, C., Willner, K. (2015b)

		Oval, empty bucket (1)	Oval, empty bucket (7b)	Oval, full bucket (2)	Oval, full bucket (7a)	Hill cycle (3)	Short transport (4)	Medium transport (6a)	Long transport (6b)
Conformity Factor	CO	n.d	0,03	n.d	0,01	0,02	n.d	n.d	n.d
Conformity Factor	THC	0,03	0,11	0,03	0,09	0,08	0,02	0,08	0,08
Conformity Factor	NOx	1,11	1,52	0,15	0,22	0,35	1,04	1,29	0,26

Analysis of the different test cycles

Oval, empty bucket

Even though the test is not a “cold start test”, the initial exhaust gas temperature is low compared to the other tests which cause high initial NO_X-emissions. Most NO_X-emissions are emitted during the first 800 seconds. The NO_X emissions are slightly higher throughout the whole test compared to the other tests on the oval. The 3 minutes idle period is too short to cause any NO_X increase, however is it classified as a non-working event and a very short part is removed.

Oval, empty bucket

Most of the NO_X emissions reflected in the test result are produced during and after the 30 minutes long idle period. The non-working events exclusion identifies the 30 minutes idle period as a long non-working event and excludes 4 minutes take-off-emissions in Evaluation method 1. When the idle period starts, it takes about 9 minutes before the exhaust gas temperature has dropped enough for the SCR to start to loose activity and the NO_X starts to increase. The NO_X -level continues to increase for about 8 minutes before it stabilizes. After the 30 minutes idle period, it takes approximately 15 minutes for the exhaust gas temperature to reach 250°C. The exhaust gas temperature stops to decrease as soon as the machine leaves idle, but remains on the same low temperature during the whole “soft” start.

If the 30 minutes idle period is removed from the test, the emissions of NO_X are the same as for the full-bucket tests, but slightly lower than test no 1.

The difference between the work-based and the CO_2-based approach show that these are nearly equivalent from a technical perspective. In all tests except for no. 2 the differences are relatively small. One explanation for the discrepancies might be that the work/CO_2 mass ratio varies as a function of the engine operating conditions.

Oval, full bucket

Test 2 does not include any non-working events and there is no effect of the non-working event exclusion. The NO_X -levels are low.

Oval, full bucket

Test 4 does not include any non-working events and there is no effect of the non-working event exclusion. The NO_X -levels are low.

Hill cycle

Test 3 includes 7 idle periods of various lengths. 5 non-working events are classified as “short” and 2 as “long”. Between the idle periods the engine is operated with high load up and down a hill. The temperature in the entire exhaust gas system has dropped and initially cools the exhaust before it all reaches temperature equilibrium.

Short Transport

After the 12 minutes idle period, it takes about 5 minutes for the exhaust gas temperature to reach 250°C. During the 4 minutes idle period, the exhaust gas temperature only drops a few degrees below 250. After each idle period, the exhaust gas temperature continues to drop for approximately 2.5 minutes when the machine leaves idle.

Medium Transport

After the 12 minutes idle period, it takes about 4.5 minutes for the exhaust gas temperature to reach 250°C, and the same happened after 8 minutes idle period. After each idle period, the exhaust gas temperature continues to drop for approximately 2-2.5 minutes when the machine leaves idle.

Long Transport

This test includes one 4 minutes idle period which is identified as a short non-working event. The NO_X increase after the event is minor, and has very little influence on the conformity factor.

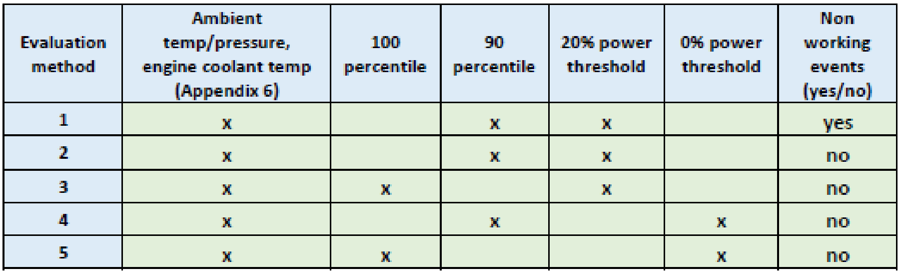
Regeneration (during long transport, carry load cycle)

The Diesel Particulate Filter (DPF) uses both passive and active regeneration strategy. The passive regeneration occurs regularly when the temperature in the DPF is sufficient. The active regeneration (PM and Sulphur removal), occurs every 100-500 hours. Regeneration does not influence emissions of THC and CO significantly, but the NO_X emissions increase considerable.

Effect of data exclusion

Similar to the previously presented study “On-board emission measurement on three wheel loaders” the effect of the different data exclusions in the proposal for In-Service Conformity for NRMM was tested by using five different calculation methods. In Table 9 different evaluation combinations are presented, where Evaluation method 1 represents the officially proposed NRMM-method. According to this method, the conformity factor should be calculated by using the 90% cumulative percentile of the respective emission component. Also, a 20% power threshold should be applied, where the average power has to exceed 20% for the work window to be considered as valid.

Table 9. Evaluation combinations and their differences with respect to data exclusion, Sandström Dahl, C., Willner, K. (2015b).



Evaluation method	Ambient temp/pressure, engine coolant temp (Appendix 6)	100 percentile	90 percentile	20% power threshold	0% power threshold	Non working events (yes/no)
1	x		x	x		yes
2	x		x	x		no
3	x	x		x		no
4	x		x		x	no
5	x	x			x	no

The effect of the removal of non-working events can be studied by comparing evaluation method 1 and 2. Method 2 and 3 compares the effect of removing the windows with the highest values. The 20% power threshold is not applied in method 4; whereas in method 5 there are no removal of high values nor removal in regards to the power threshold. It is however important to remember that the effect of removal of non-working events are depending on the driving cycle. For the wheel loaders tested in this project, the machines were tested at high loads with very short periods of idling.

Result from both studies

The overall performance of the NO_X- emissions from the three loaders in Sweden (with 3 emission standards) is shown in the Figure 34. Emissions are expressed in g/h as a function of engine power (kW), divided by emission standard (colour). The emission limits (Stage IIIA-IIIB-IV) are represented as solid lines. Stage IIIA has no line since the standard is expressed as NO_X + HC. The picture is indicative and should be interpreted with caution.

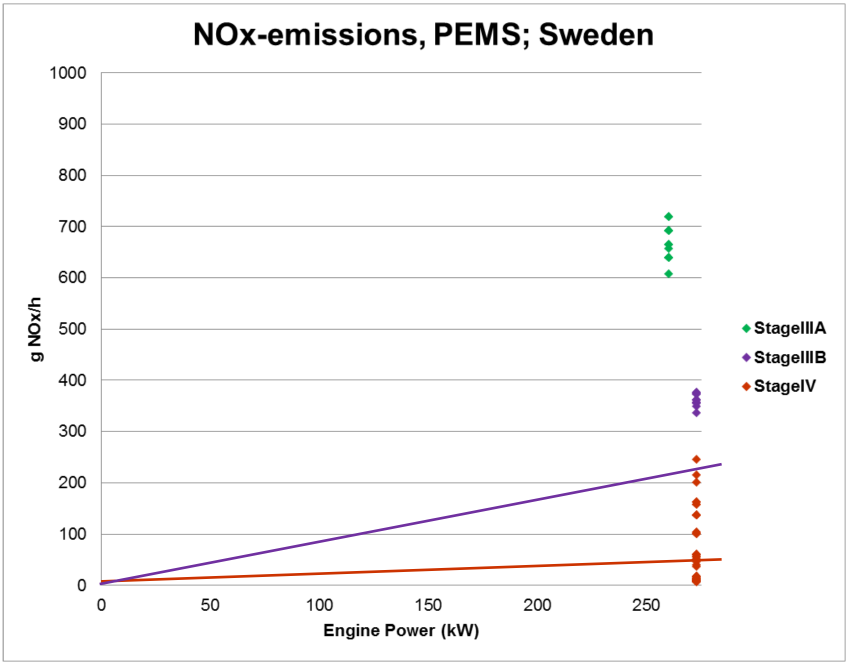


Figure 34. NOX –emissions expressed in g/h as a function of engine power, divided by emission standard (identified by colour). The solid lines represent the emission standards. Dots below the solid lines (with the same color) represent legal compliance, dots above the lines non-compliance. Stage IIIA has no line since the standard is expressed as NOX + HC. The figure should be considered indicative.

Conclusion

When comparing the three machines in relation to their emission standards, the result is very consistent; Stage IIIA has higher emissions, followed by Stage IIIB and last Stage IV (NO_X). The measurement result show that the different work operations play an important role for the emission levels (second study), while different evaluation methods (1-5) in general play a smaller role.

Regarding the control technologies the result from Sweden confirm earlier conclusions, that SCR and DPF are very strong tools to reduce NO_X and PM emissions respectively, and EGR has no effect on NO_X. None of the three loaders tested in Sweden had DOC installed.

Finland

Introduction

The Finnish contribution consists of measurements using both engine bench and on-board measurements. Two different fuels were used; current EN590 diesel containing 7% FAME; and HVO Neste Renewable Diesel. The measurements are described below;

- Bench tests using three different four cylinder non-road engines (Stage 0, Stage IIIA and Stage IV).
- On-board measurements on two different loaders, Wille 355b and Wille 855c (both Stage IIIA) using the same fuels as used in the bench tests.
- Effect of suitable retrofit particle catalyst/trap using the oldest Stage 0 engine.

The main purpose was to study advantages of renewable high quality fuel in engines of different emission Stages. The quality of the renewable fuel is the same as HVO but only some 25-30% of the raw material is vegetable oil.

Bench tests

Tested machinery and used fuels

Tests were run using three different 4-cylinder diesel engines representing Stage 0, Stage IIIA and Stage IV. Stage 0 represents technology from time without any exhaust emissions limits. Stage IIIA level can be reached without exhaust gas after treatment devices, emissions are tested using steady state cycle although use of transient cycle is allowed but not mandatory. Stage IV represents today's engine with stringent emission limits and compulsory transient testing.

Retrofit particulate trap used in the tests with Stage 0 emission level engine was ceramic filter with coating for passive NO_2 based regeneration.

The fuels used in the tests were conventional current EN590 standard fulfilling automotive diesel fuel containing 7% fatty acid methyl ester (FAME), and hydrotreated diesel fuel Neste Renewable Diesel produced from renewable raw materials, mainly from waste and residues. Renewable fuel fulfills EN590 standard too excluding density. Cetane number of Neste Renewable Diesel is very high, final boiling point is low and it contains in practice no aromatics.

Measurement methods

Two non-road test cycles were used:

- Steady cycle (NRSC); ISO 8178 C1
- Transient cycle (NRTC); US EPA

Cold cycles were run only with Stage IV engine to find out the cold start emissions of a modern engine equipped with exhaust gas abatement devices. The weight of cold cycle is 10%, by experience it is known that repeatability is not as good as that of hot cycle[4] and only one cold cycle / day can be run. That's why cold cycles were not run with Stage 0 and Stage IIIA engines. NRSC and NRTC hot cycle results are average of two test run, NRTC cold cycle was run only once with each fuel.

Regulated exhaust emissions were measured and calculated over the test cycle (CO, THC, NO_X, PM, CO_2) as well as fuel consumption (FC). Measurements were conducted using devices fulfilling the requirements given by the emission standards.

Result

Stage 0

Nitrogen oxide emissions were clearly over Stage I limit, 9.2 g/kWh, but all other emissions were reasonably low, clearly under Stage I limits. CO_2 emissions were lower than those of the Stage IIIA and Stage IV engines.

Transient cycle gave more particulate mass and less NO_X than steady cycle. Compared to conventional diesel fuel Neste Renewable Diesel reduced PM

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[4] Matti Kytö, VTT, Engines and emissions team, Finland.

emissions some 30% and NO_X emissions 7-8%. CO and HC emissions were reduced clearly too. Particulate trap reduced particulate mass emission dramatically as well as CO and HC emission. PM emission with trap was clearly lower than current limit for Stage IV engines. Trap had no influence to NO_X emission.

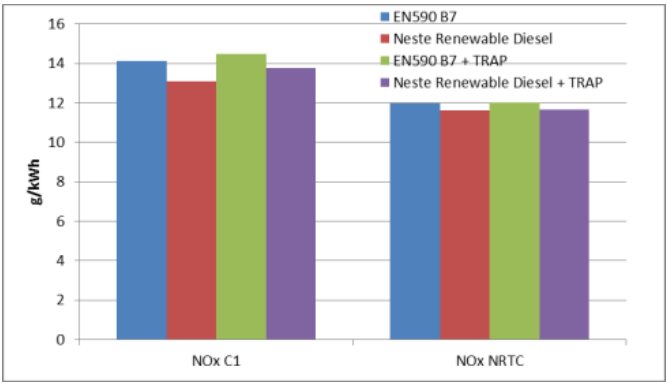

Figure 35. NO_X emissions of Valmet DS411 Stage 0 engine at steady (C1) and transient (NRTC) cycles, Kytö M., Söderström C., Westerholm M. (2017).

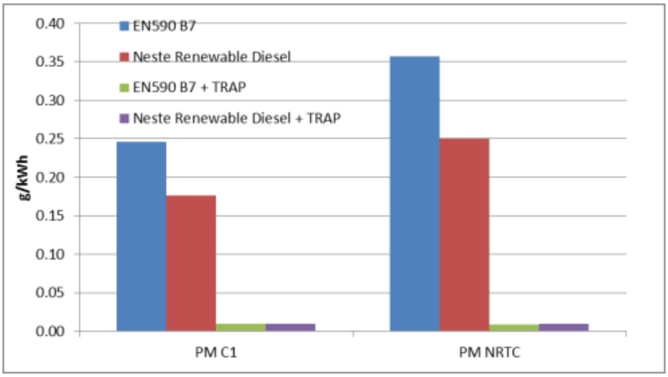

Figure 36. PM emissions of Valmet DS411 Stage 0 engine at steady (C1) and transient (NRTC) cycles, Kytö M., Söderström C., Westerholm M. (2017).

Stage IIIA

Compared to the Stage 0 engine the Stage IIIA engine's common rail fuel system is the most remarkable difference affecting the exhaust emissions. Common rail enables injection timing optimization over the loading point area. All emissions were clearly under Stage IIIA. NO_X emissions were roughly two thirds lower than those of the Stage 0 engine and PM levels were 50 – 65% lower. Compared to conventional diesel, the Neste Renewable Diesel reduced PM emissions 24- 31% and NO_X emissions 2-4%.

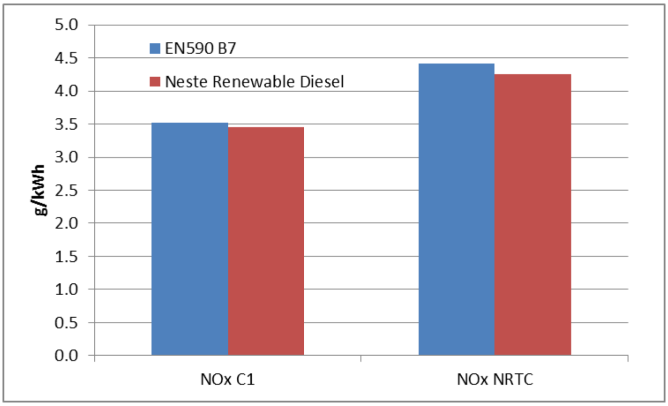

Figure 37. NO_X emissions of AGCO Power 44CW3 Stage IIIA engine at steady (C1) and transient (NRTC) cycles, Kytö M., Söderström C., Westerholm M. (2017).

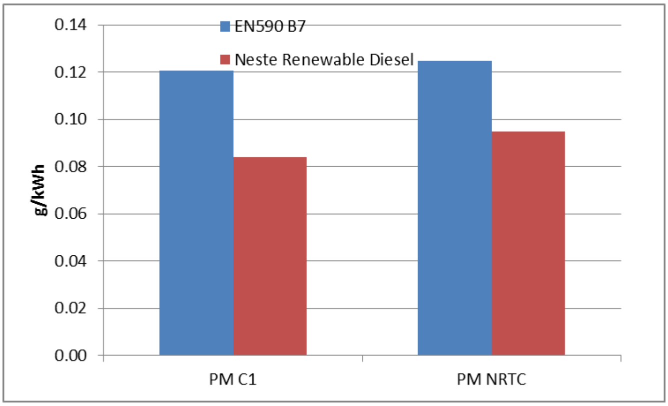

Figure 38. PM emissions of AGCO Power 44CW3 Stage IIIA engine at steady (C1) and transient (NRTC) cycles, Kytö M., Söderström C., Westerholm M. (2017).

Stage IV

All emissions were clearly under Stage IV limits. Neste Renewable Diesel reduced PM and NO_X emissions during hot cycles but increased on cold cycle. Since the cold cycle was run only once, the NO_X result has to be taken as indicative only.

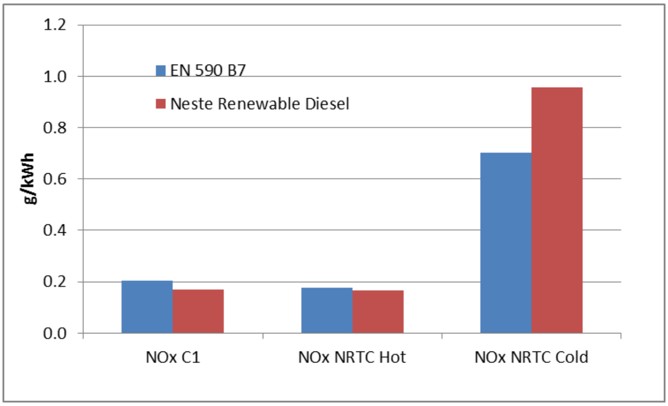

Figure 39 NOx emissions of AGCO Power 44AWFC Stage IV engine at steady (C1) and transient (NRTC) cycles, Kytö M., Söderström C., Westerholm M. (2017).

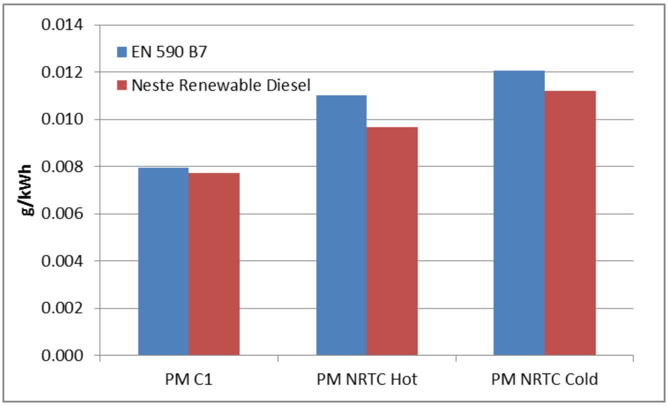

Figure 40. PM emissions of AGCO Power 44AWFC Stage IV engine at steady (C1) and transient (NRTC) cycles, Kytö M., Söderström C., Westerholm M. (2017).

On-board measurements

Tested machinery

The two measured machines were loaders with Stage IIIA emission level engine; Wille 355b and Wille 855c. They were measured with the same fuels as used in the bench tests. The loaders are owned and used by Stara, the construction service of the City of Helsinki. The loaders differed in terms of size and engine technology although the emission standard was the same.

Measurement methods

Drivers were interviewed to find out typical use of the machines and test cycle was built to consist parts of most common driving/working conditions. Four test sequences were taken to the cycle, sequences were:

1. Idling
2. Transportation, depicting driving from depot to working area and back
3. Plowing, additional drive resistance was simulated by dragging a blast mat behind the test vehicle (extra load to simulate snow plowing)
4. Loading of goods

Idling and preparation times were fixed, all other sequences were repeated as equally as possible every time but not within fixed time. Tests were performed twice on both fuels and reported results are the average results of two complete test runs. Test platform was a closed gravel surfaced field near the machine depot.

Measurements were conducted with two different measurement systems. Both systems sampled emissions from the exhaust pipe. Gaseous emissions and the exhaust flow rate were measured by Neste with Horiba PEMS. Gas Analyzers of the PEMS were calibrated before and after each measurement using calibrating gases. Particle emissions were measured with a TUT-PEMS[5].

In this application, the particle measurement setup consisted of:

- Two-stage ejector dilution, primary being heated to 140 ºC. The dilutors were installed directly to the exhaust pipe. The total dilution ratio (DR) was 150 confirmed by CO2 measurements.
- Particle concentration and size distribution measurement using Condensation Particle Counter (A20, Airmodus Oy) and Engine Exhaust Particle Sizer (EEPS 3090, TSI Inc.). Size distribution was used to calculate mass emission (particle effective density 1 g/cm3 assumed).

Results

Some differences occurred between the test runs on the two fuels and in conclusion the engine did not operate on comparable engine load points after fuel was changed. Therefore raw exhaust gas emissions are not directly comparable, and thus gaseous emissions were normalized to consumed fuel energy. The test result is shown in the Table 10 below:

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[5] Tampere University of Technology (TUT) (http://www.nanoparticles.ch/2015_ETH-NPC-19/Poster/35_Jaervinen_Anssi.pdf)

Table 10. Result from on-boards measurements when comparing fossil diesel and renewable diesel, absolute and relative change (%).

	Fossil diesel (EN 590 B7)	**Renewable diesel**	**Change (%)**
Wille 355			
CO	0.7	0.09	-87
HC	0.06	0.04	-35
NO_X	1.1	1.2	+8
CO2	265	260	-2
Wille 855			
CO	0.005	0.004	-20
HC	0.09	0.07	-14
NO_X	1	0.9	-11
CO2	265	254	-4

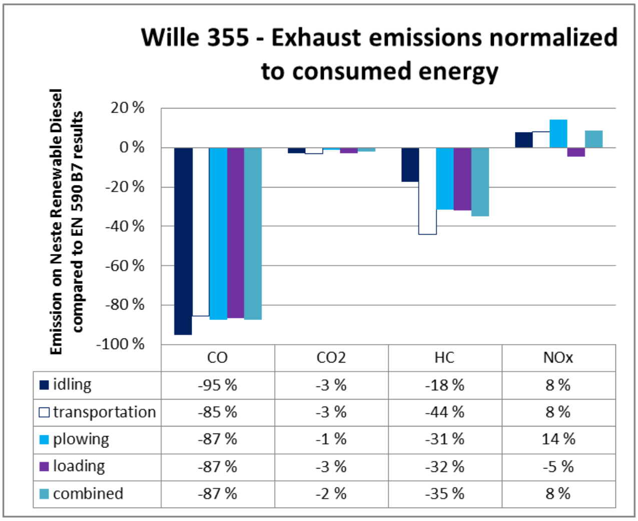
Wille 355

Neste Renewable Diesel reduced CO emissions on loader tests clearly more than on engine tests with Stage IIIA emission level engine. Most probably the reason is different engine technology, naturally aspirated engine with distributor fuel pump versus turbocharged common rail engine. Compared to Stage II, NO_X limit is lower, CO limit is the same. CO emission in engine test was only about 15% of the limit.

HC reduction was clear in all tests. Reduction in percentage varies a lot but at least one reason to that is the fact that absolute HC emission is low.

Engine tests showed that Neste Renewable Diesel gives small reduction of NO_X emission too. That was not the case on loader test but reason for that can be variability between tests.

CO_2 reduction was the same over all tests. Both fuel consumption and H/C ratio of the fuel effect the CO_2 emission.

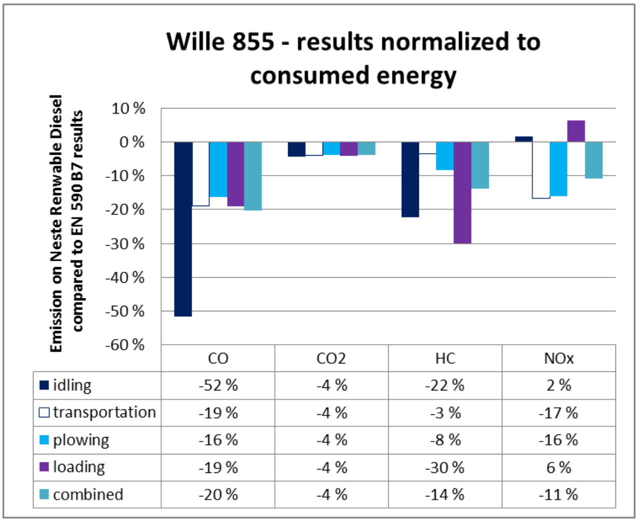


	CO	CO2	HC	NOx
■ idling	-95 %	-3 %	-18 %	8 %
☐ transportation	-85 %	-3 %	-44 %	8 %
■ plowing	-87 %	-1 %	-31 %	14 %
■ loading	-87 %	-3 %	-32 %	-5 %
■ combined	-87 %	-2 %	-35 %	8 %

Figure 41. Emission differences of Wille 355 tests with Renewable Diesel compared to conventional diesel. Results are corrected according to energy consumption, Kytö M., Söderström C., Westerholm M. (2017).

Wille 855

Neste Renewable Diesel reduced CO emissions on Wille 855 tests clearly more than on engine tests with Stage IIIA emission level engine but clearly less that on Wille 355 tests. Although the emission classification of the engines is the same Wille 355 engine is the only naturally aspirated one and represents somewhat older technology then the others. Average NO_X reduction was 11% which is more than on engine tests. HC reduction in percentages was smaller than in other tests.



	CO	CO2	HC	NOx
■ idling	-52 %	-4 %	-22 %	2 %
☐ transportation	-19 %	-4 %	-3 %	-17 %
■ plowing	-16 %	-4 %	-8 %	-16 %
■ loading	-19 %	-4 %	-30 %	6 %
■ combined	-20 %	-4 %	-14 %	-11 %

Figure 42. Emission differences of Wille 855 tests with Renewable Diesel compared to conventional diesel. Results are corrected according to energy consumption, Kytö M., Söderström C., Westerholm M. (2017).

Particle emissions

Particle number concentration and size distribution were the main monitored values. Particle mass (PM) was calculated from the size distributions using 1 g/cm^3 as effective density. Results of particle measurements are presented in a conference (Järvinen et al. 2015).

Measurement devices diagnosed concentration and size distribution of particles:

- Condensing Particle Sizer (CPC) Airmodus A20, particles over 7 nm diameter
- Engine Exhaust Particle Sizer (EEPS 3090, TSI Inc), 5.6-560 nm particles

On average the CPC gave a little higher concentration than the EEPS. During idling the number of particles was low, during two driving periods without load the particle concentration increased from idle level clearly and was not stable unlike driving periods with extra load (plowing). Concentration during two minute loading period was between idle and driving periods.

Effects of fuel on particle concentration can be seen from Table 11. Generally Neste Renewable Diesel decreased the number of particles at idle, with Wille 355 at plowing mode too. At both operation modes the difference results mostly from the reduction of concentration at very small particles. Neste Renewable Diesel produced clearly less calculated particle mass than conventional diesel in all cases, the reduction in particle mass was bigger than that in number of particulates. Reason for this is that the particle size is smaller in the case of the Neste Renewable Diesel.

Table 11. Effect of fuel to number of particles and PM results are normalized for energy use. Changes are calculated using units #/(kWh_fuel) and mg/(kWh_fuel). Percentages shown mean change of emission when change fuel, Kytö M., Söderström C., Westerholm M. (2017).

Machine	Cycle point	Number of particles, change EN 590 => Renewable Diesel (%)	Particle mass, change EN 590 => Renewable Diesel (%)
Wille 855	Idling	-65	-35
	Transportation	-3	-25
	Plowing	+6	-22
	Loading	-6	-25
Wille 355	Idling	-26	-35
	Transportation	-7	-55
	Plowing	-22	-58
	Loading	+48	-28

Machine	Cycle point	Number of particles, change EN 590 => Renewable Diesel (%)	Particle mass, change EN 590 => Renewable Diesel (%)
Wille 855	Idling	-65	-35
	Transportation	-3	-25
	Plowing	+6	-22
	Loading	-6	-25
Wille 355	Idling	-26	-35
	Transportation	-7	-55
	Plowing	-22	-58
	Loading	+48	-28

Conclusion

Bench tests

It is possible to decrease diesel engines exhaust emissions by using high quality fuel. The older engine technology the bigger reduction potential. For newer engines NO_X is in practice often reduced using SCR and functioning of SCR system is the key to low NO_X emissions.

Compared to conventional diesel, Neste Renewable Diesel reduced PM emissions some 30% and NO_X emissions about 7 - 8% on Stage 0-emission level engine, CO and HC emissions were reduced clearly too. Particulate trap reduced PM dramatically as well as CO and HC emission. PM emission with trap was clearly lower than current limit 0.025 g/kWh for Stage IV engines. Trap had no influence to NO_X emission. On Stage IIIA engine the renewable diesel reduced PM emissions 24 - 31%, similar as Stage 0 engine. With the Stage IV, PM emission reduction could still be seen but the absolute reduction at NO_X was very small.

High quality fuel reduced clearly PM emissions and to some extent NO_X in cases the engine had no exhaust gas aftertreatment system. Retrofit particulate trap proved to be a very effective to reduce PM of Stage 0 – IIIA.

HVO as a fuel will not solve the problem with NO_X, even though the percentual/relative reduction may be considerable, the absolute numbers are to small and the uncertainties to significant.

Concerning PM emissions, the reduction when using HVO fuel is deemed as moderate, and to achieve a more crucial PM emission reduction, a particle filter (here called “trap”) is still needed.

On- board measurements

Accuracy and repeatability of these measurements is not comparable to laboratory measurements. Due to some test-to-test variability emission results were corrected according to energy consumption. Neste Renewable Diesel has clear positive influence on CO and HC emissions.

Neste Renewable Diesel caused higher CO and HC emission reduction on traditional distributor pump of (CO -87%, HC -34%) than on contemporary turbo charged common rail (CO -18%, HC -12%). CO and HC reduction could be seen in all sequences, from idling to plowing.

Neste Renewable Diesel increased NO_X emission on Wille 355 and decreased them on Wille 855. One reason is test-to-test variability of hand throttle position. On relatively stable loads (transportation, plowing) there was NO_X reduction, while on unstable loads like idling and loading NO_X increases (Wille 855). Possibly energy consumption correction does not compensate well enough the NO_X-emission change caused by load change. Small reduction on CO_2 emission (1-4%) was seen in all measurements in favour of Neste Renewable Diesel.

Reduction of particle number emissions was high at idle (and at loading with smaller loading) with renewable fuel. PM reduction was observed for both loaders during all activities, which results from the smaller average particle size, which may be a result of a higher cetane number; 79 vs. 57 and a lower aromatic content 0.3 vs. 15 wt-%.

Comparison of data from all countries

The measurement part of the Annex 50 project has been carried out in collaboration with institutions in different countries, and measurement data has been delivered from four countries: Sweden, Finland, Canada and Switzerland. The datasets are however very different in the sense of measurement methods, test cycles, data evaluation methods, parameters analyzed, extent, actuality, and supplied attached information. Additionally to all this, the measured objects (the NRMMs) comprise a wide range of equipment and characteristics with respect non-road category, machinery size, engine power class, emission standard, fuel type used in the measurement, fuel injection system, exhaust gas abatement equipment, machinery operated hours and more. Comparisons of measurement data between countries in this case are therefore deemed as irrelevant and could in that case be misunderstood.

However, a rough analysis of NO_X-emission factors (g/kWh) in Sweden, Finland, Switzerland and Canada from NRMM with respect to power class and emission standard is showed in Figure 43. The colors differentiate the emission standards (Stages) as well as the "NO_X-retrofitted" old machines.

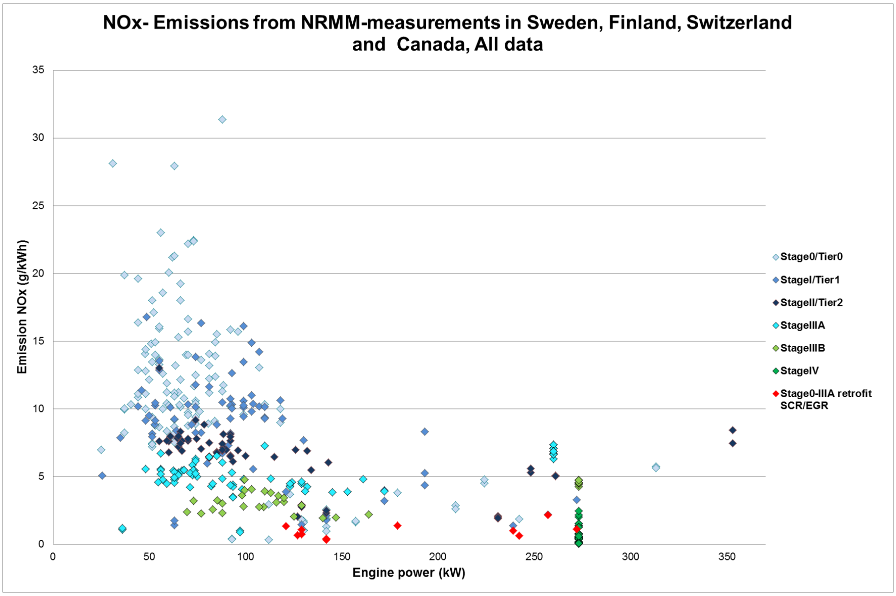


Figure 43. Illustration of NOx- emission factors when assembling all observed measurement data from four countries. The data is divided by emission standards (colors) and old machinery retrofitted for NOx-reduction.

The influence of control technologies was also evaluated; the result is shown in the Figure 44. Data from three countries is assembled.

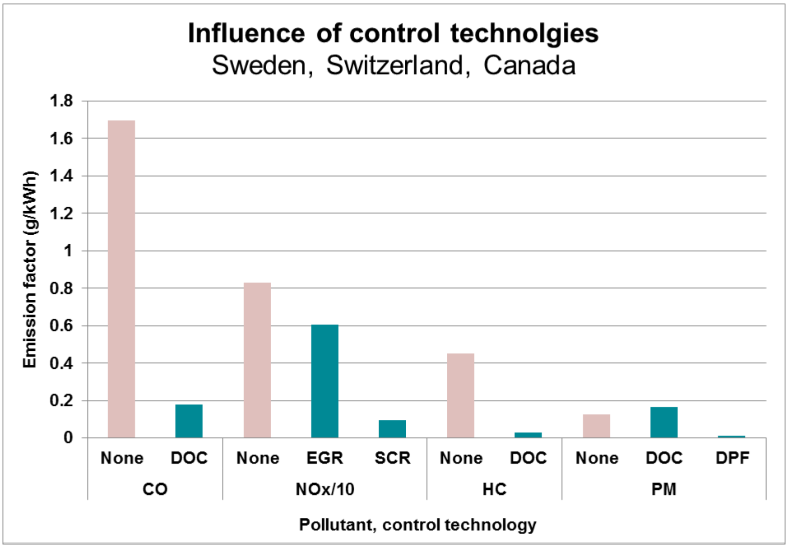


Figure 44. Influence of control technologies at NO$_X$-emission non-road mobile machinery, data assembled for three countries.

Conclusions

When evaluating data from all four countries (Sweden, Finland, Canada and Switzerland), the key findings are;

- The overall picture of the assessed machinery fleet with respect to NO$_X$- emissions proves a clear a consistent drop of emission per energy unit for NRMM when comparing the emission standards. The most distinct change is when moving from Stage II to Stage IIIA in the Swiss data- which is the most comprehensive.

- Still, the emission factors are in general slightly higher than the emission limits with the used calculation methods. This conclusion should anyway be considered with caution, since there are several uncertainties in the methodologies and the data evaluation.

- One important finding is also that the emission factors seem to be at similar level within the same emission standard, regardless of the engine power.

- The Swedish measurements only analysed three individuals, but is the most complex with respect to real-life test cycles. The emission points for different cycles are in general relatively concentrated and confirm previous conclusions.

- Information about control technologies was not complete but in general relatively satisfactory. The use of control technologies reveals that DOC strongly reduce CO and HC-emissions, but has no clear effect on PM. EGR has a clear but relatively modest effect on NO_X while SCR is a very strong tool to reduce the NO_X-emissions. The magnitude of the NO_X reduction effectiveness of EGR varied somewhat between the different studies.

- DPF is the most effective way to reduce particle emissions and will be necessary to comply with future regulations. If SCR and DPF are combined, it seems to result in strongly decreased emissions of CO and HC as well.

- Retrofitted (old) machinery seems to perform as good as new equipment with respect to emissions, if similar aftertreatment technologies are used.
- To use diesel-water emulsion seems to have certain effect on NO_X and PM, though not particularly distinct. Tested biofuels impact on NO_X- emissions (in relation to conventional diesel) is unclear.

- No clear conclusion was drawn from the analysis of machinery ageing in the Swiss measurement data.

Simulation of machinery fuel and energy consumption

Introduction

The objective in this study was to develop a machine level simulation model to study the energy consumption of a wheel loader during a working cycle. The simulation model focuses on the powertrain and the boom and bucket hydraulic system.

Method

The energy efficiency of NRMM can be enhanced by using new technical innovations, and one promising aspect for increased energy efficiency is to electrify the powertrain. Electrification is the most suitable where the average power consumption is low, but the peak powers are high. Therefore, the engine has to be dimensioned by the peak power demand.

A simulation model was used which enables the energy consumption definition for different powertrain concepts and working cycles. The studied wheel loader is a typical and generic medium-duty loader.

Typical working cycles of a wheel loader are variable, for example earth moving and material handling in industrial use. A computer simulation was used to study its dynamic behavior. The simulation model of the wheel loader includes all the main energy systems;

1. Vehicle model
2. Powertrain model
3. Hydraulic System Model
4. Working Cycle Model

They are explained in the following:

1. Vehicle model

The longitudinal dynamic model defines the motion of the machinery body under the working cycle. The model of the loader body calculates axle loadings, which are fed to the tire model. The tire model defines the longitudinal force developed by the tire as a function of tire slip and normal force and takes the rolling resistance into account, see Figure 45.

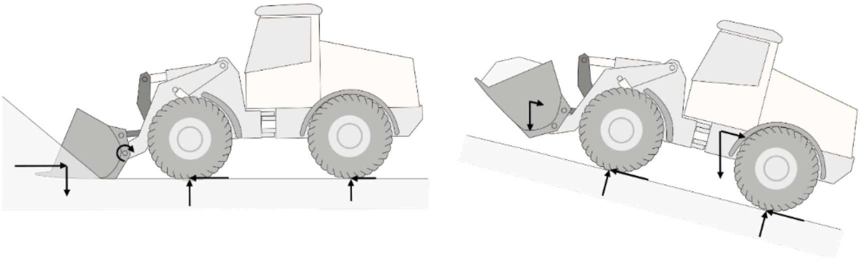


Figure 45. Forces acting on the wheel loader during bucket filling and driving in a slope.

2. Powertrain model

The works for which wheel loaders are designed require high tractive force, also at low speeds. To fulfill this requirement, conventional wheel loaders have a hydrostatic or hydrodynamic powertrain.

Typically, in a hydrostatic powertrain a diesel engine runs a hydraulic pump, which is connected to a hydraulic motor to run the wheels. With hydrodynamic powertrain, the diesel engine is connected to the mechanical driveline using torque converter, and the torque converter also serves an infinitely variable ratio which is needed for a wheel loader working. The mechanical drivetrain usually has a powershift type of gearbox.

In the study two different and simulated powertrain configurations were modelled; conventional hydrodynamic powertrain and electric direct drive powertrain. The traditional powertrain consists of a diesel engine connected to the mechanical driveline using a torque converter. The electrified powertrain has an electric traction motor connected directly to the mechanical driveline. The mechanical drivetrain consists of a reduction gear, which also splits the driveline to front and rear axles. Consequently, the simulation is not optimized to evaluate a wholly electrified powertrain.

3. Hydraulic System Model

Another main power consumer of the wheel loader is the hydraulically actuated boom and bucket system. It has a Z-bar linkage, which ensures a high breakout force and is suitable especially for earth moving applications. The force acting on the bucket is transferred to the bucket cylinder forces using dimensions of the bucket mechanism. Using the control signals to the bucket and boom, the hydraulic flow to the cylinders can be defined. Cylinder forces and flow can be used to define the power consumption of the hydraulic system.

4. Working Cycle Model

A typical task of a wheel loader was studied, and included filling and tipping the bucket. The working cycle is divided into more detailed phases, driving towards the bank (1), driving against bank to fill the bucket (2), reversing from the bank (3), driving towards the tipper truck and lifting the bucket (4), tipping the bucket load (5), reversing from the truck (6), and then driving towards the bank again. When plotted as a speed and distance, the working cycle looks like shown in Figure 46.

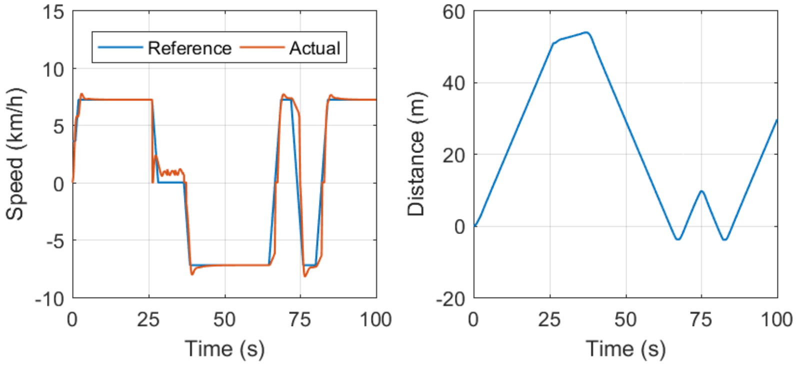


Figure 46. Loader speed and distance during the working cycle.

The simulation model includes an interaction model that calculates the force acting on the bucket. The force depends on the bucket dimensions, material properties, and the location of the bucket. Parameters of the interaction model are adjusted to give a bucket filling factor around 100%.

Result

Simulation results show that the power consumption varies a lot during the working cycle and it is high especially at bucket filling phase and bucket tipping phase, and in the change of loader driving direction. Total energy consumptions of the studied wheel loaders are not directly comparable because of different control actions and therefore different amount of work done during the bucket filling.

In the case of the conventional wheel loader, the work done for the traction is 1.7 MJ and for the hydraulic system 0.77 MJ. The average power needed from the diesel engine is 36 kW.

In the case of the electric wheel loader, the work done for the traction is 1.4 MJ and for the hydraulic system 0.94 MJ. The average power needed from the electric engine is 16 kW.

Conclusion

A computer simulation is a powerful tool for studying the behavior of dynamic systems. The simulation approach proposed can be used to define the energy consumption during a working cycle. If the simulation model is augmented by the steering system, or it is done in 3D using multibody system simulation, the working cycle could be simulated in even more detail. This kind of simulation model could be used to find optimal trajectories and loading schemes.

The energy efficiency of NRMM can be improved especially in cases where high torques is needed at low speeds. With conventional drivelines done using hydrodynamic or hydrostatic approaches, the losses are much higher compared to electric one especially when the loader is pushing towards to stock with high torque and low speed. On the other hand, with the electric powertrain the regenerative braking can be used to store kinetic energy into the energy storage, which makes the energy efficiency even better..

In the case of a diesel-electric powertrain with no energy storage on-board, regeneration power can still be exploited at some level, which makes the diesel load smaller. On the other hand, using the electric drive the response for the driving actions can be more immediate, when the flexible torque converter is not present in the driveline.

To be able to simulate the wheel loader energy consumption realistically, the work cycle has to be included. An interaction model was developed and used to calculate forces acting on the bucket and this kind of model is needed, if different driving styles will be simulated. The interaction model can be changed to predict interaction forces for some other material by adjusting model parameters.

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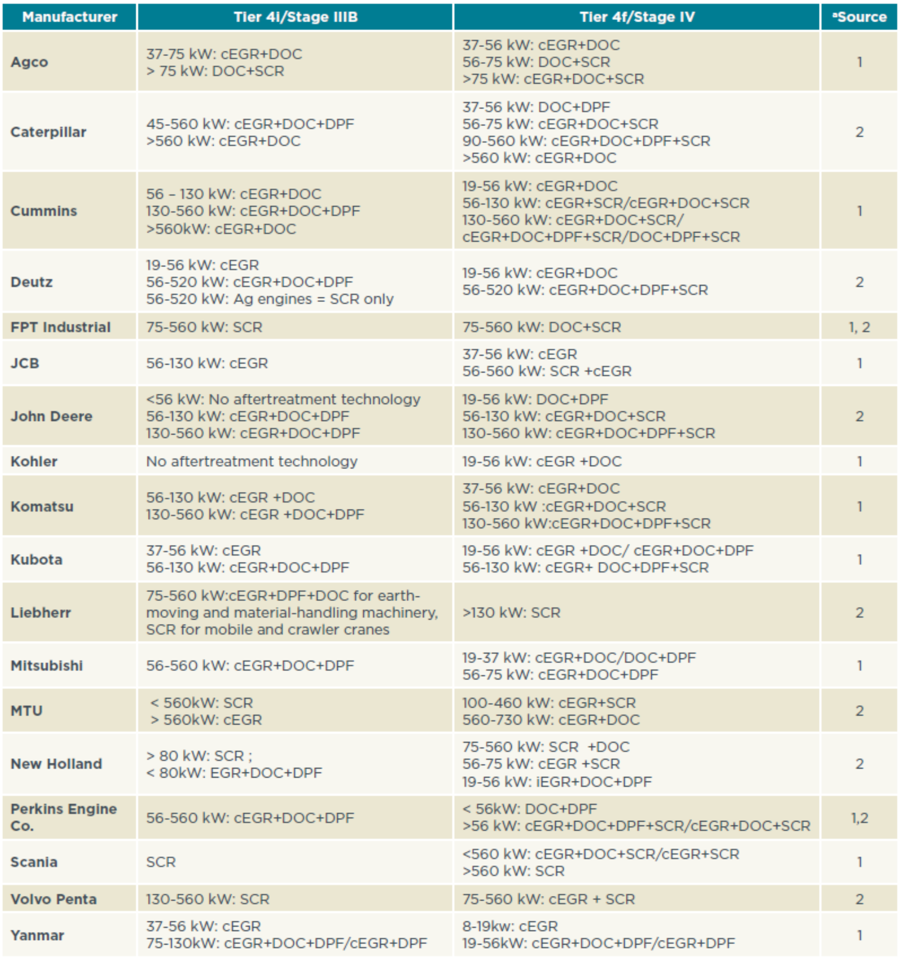
Annex 1

Tier 4i/Stage IIIB and Tier 4f/Stage IV emission control technology packages for major non-road engine manufacturers (ICCT (2016).



Manufacturer	Tier 4i/Stage IIIB	Tier 4f/Stage IV	[a]Source
Agco	37-75 kW: cEGR+DOC > 75 kW: DOC+SCR	37-56 kW: cEGR+DOC 56-75 kW: DOC+SCR >75 kW: cEGR+DOC+SCR	1
Caterpillar	45-560 kW: cEGR+DOC+DPF >560 kW: cEGR+DOC	37-56 kW: DOC+DPF 56-75 kW: cEGR+DOC+SCR 90-560 kW: cEGR+DOC+DPF+SCR >560 kW: cEGR+DOC	2
Cummins	56 – 130 kW: cEGR+DOC 130-560 kW: cEGR+DOC+DPF >560kW: cEGR+DOC	19-56 kW: cEGR+DOC 56-130 kW: cEGR+SCR/cEGR+DOC+SCR 130-560 kW: cEGR+DOC+SCR/ cEGR+DOC+DPF+SCR/DOC+DPF+SCR	1
Deutz	19-56 kW: cEGR 56-520 kW: cEGR+DOC+DPF 56-520 kW: Ag engines = SCR only	19-56 kW: cEGR+DOC 56-520 kW: cEGR+DOC+DPF+SCR	2
FPT Industrial	75-560 kW: SCR	75-560 kW: DOC+SCR	1, 2
JCB	56-130 kW: cEGR	37-56 kW: cEGR 56-560 kW: SCR +cEGR	1
John Deere	<56 kW: No aftertreatment technology 56-130 kW: cEGR+DOC+DPF 130-560 kW: cEGR+DOC+DPF	19-56 kW: DOC+DPF 56-130 kW: cEGR+DOC+SCR 130-560 kW: cEGR+DOC+DPF+SCR	2
Kohler	No aftertreatment technology	19-56 kW: cEGR +DOC	1
Komatsu	56-130 kW: cEGR +DOC 130-560 kW: cEGR +DOC+DPF	37-56 kW: cEGR+DOC 56-130 kW :cEGR+DOC+SCR 130-560 kW:cEGR+DOC+DPF+SCR	1
Kubota	37-56 kW: cEGR 56-130 kW: cEGR+DOC+DPF	19-56 kW: cEGR +DOC/ cEGR+DOC+DPF 56-130 kW: cEGR+ DOC+DPF+SCR	1
Liebherr	75-560 kW:cEGR+DPF+DOC for earth-moving and material-handling machinery, SCR for mobile and crawler cranes	>130 kW: SCR	2
Mitsubishi	56-560 kW: cEGR+DOC+DPF	19-37 kW: cEGR+DOC/DOC+DPF 56-75 kW: cEGR+DOC+DPF	1
MTU	< 560kW: SCR > 560kW: cEGR	100-460 kW: cEGR+SCR 560-730 kW: cEGR+DOC	2
New Holland	> 80 kW: SCR ; < 80kW: EGR+DOC+DPF	75-560 kW: SCR +DOC 56-75 kW: cEGR +SCR 19-56 kW: iEGR+DOC+DPF	2
Perkins Engine Co.	56-560 kW: cEGR+DOC+DPF	< 56kW: DOC+DPF >56 kW: cEGR+DOC+DPF+SCR/cEGR+DOC+SCR	1,2
Scania	SCR	<560 kW: cEGR+DOC+SCR/cEGR+SCR >560 kW: SCR	1
Volvo Penta	130-560 kW: SCR	75-560 kW: cEGR + SCR	2
Yanmar	37-56 kW: cEGR 75-130kW: cEGR+DOC+DPF/cEGR+DPF	8-19kw: cEGR 19-56kW: cEGR+DOC+DPF/cEGR+DPF	1