Emission Factor Model for Construction Machinery Based on PEMS Tests

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Introduction and Motivation

Currently, the emission behavior of vehicles in real world driving (passenger cars, commercial vehicles, two-wheeled) can be mapped well with the Handbook of Emission Factors for Road Transport (HABEFA). The handbook is structured according to different vehicle categories and emission classes and defines typical real world driving conditions. For each driving condition emission factors for the individual emission components per vehicle category are assigned.

However, this is not the case for non-road vehicles. The emission assessment for mobile machinery is based almost exclusively on data from the engine tests during type testing. As the emission behavior of modern, electronically controlled engines in real world engine operation can be very different from the type approval values obtained during type testing, the emission measurements were performed in real world machinery operation to validate the emission data used up to now and to adapt it, if necessary. The measurements were then used to map the emission behavior during real world operation. Furthermore, an attempt was made to establish a method for calculating the emission factors of construction equipment.

Emission Classes of Non-Road Vehicles

Whereas emission legislation for heavy duty vehicles has existed since 1993, emission limits for non-road vehicles were first defined in 1999. Figure 1 shows the development of the limits since 1993.

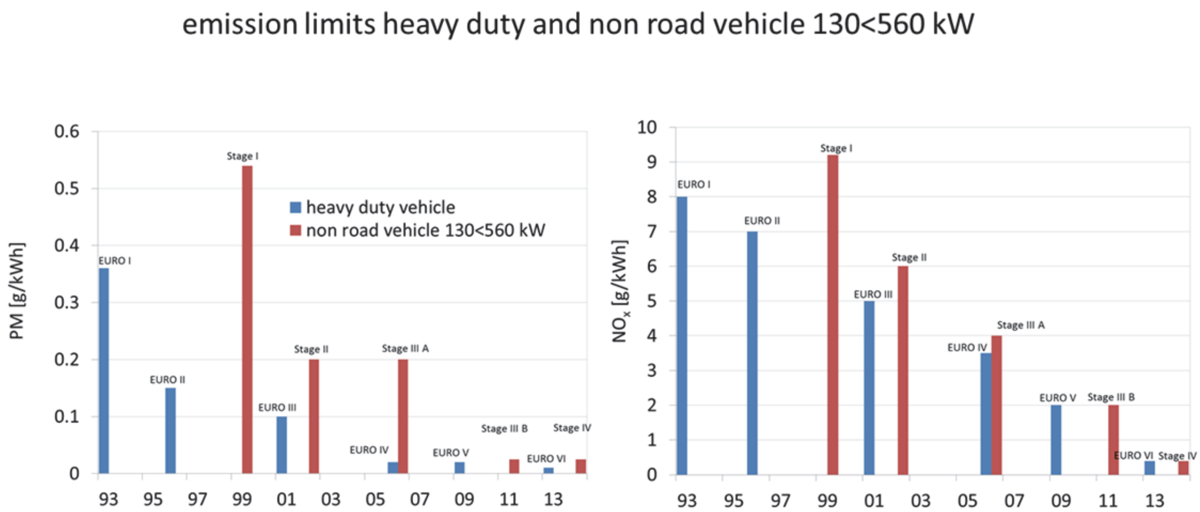


Figure 1: Emission limits for heavy duty vehicles and for non-road machines (130<560 kW)

Methodology

In a project founded by the Austrian Ministry of Environment 17 machines were measured with an on-board measuring system. The analysis showed that different machines during working operation are operated partly in very different areas of the engine map. Figure 2 shows typical load points (torque/engine speed) driven during the NRTC Cycle in comparison to load points of different types of construction machines in real world operation (circled in the map).

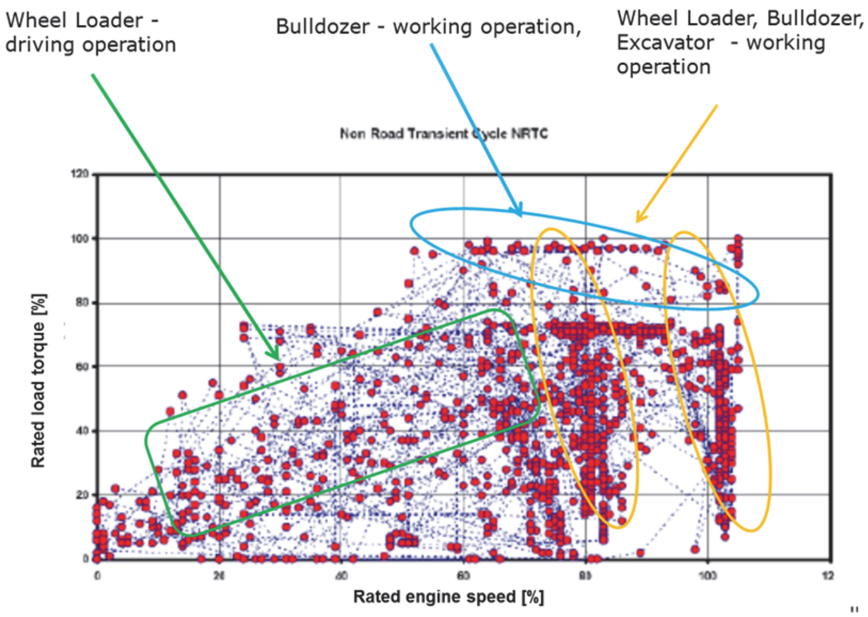


Figure 2: *Example for load points in the NRTC Cycle and in real world operation*

In order to cover a broad as possible map range of engines with the measurements, the vehicle categories in Table 1 were examined in this project. All of the machines in emission class III B, except for a hybrid excavator, were equipped with exhaust after-treatment systems. These consisted of an oxidation catalyst and a diesel particle filter.

Table 1: Overview of measured construction machinery

vehicle categorie	7.5 to excavator	20 to excavator	wheel loader	mini digger	road roller
measured emission classes	Stage I	Stage I	-	-	-
	Stage II	Stage II	Stage II	Stage II	-
	Stage III A	Stage III A	Stage III A	Stage III A	-
	Stage III B	Stage III B	Stage III B		Stage III B

Figure 3: Measurement setup

The measurements were performed in typical use situations for each machine. For the excavators, it was the moving of loose material; for the wheel loaders it was stripping work in a gravel pit; and for the drum roller (road roller), it was rolling on a forest road.

Each machine was measured for 20 minutes. Three measurements were performed for each construction machine.

Each machine was equipped with an onboard measuring system (Sensors' Semtech DS and AVL Micro Soot Sensor). This measuring system allowed the gaseous emissions CO_2, CO, THC and NO_x (NO and NO_2) as well as soot to be measured.

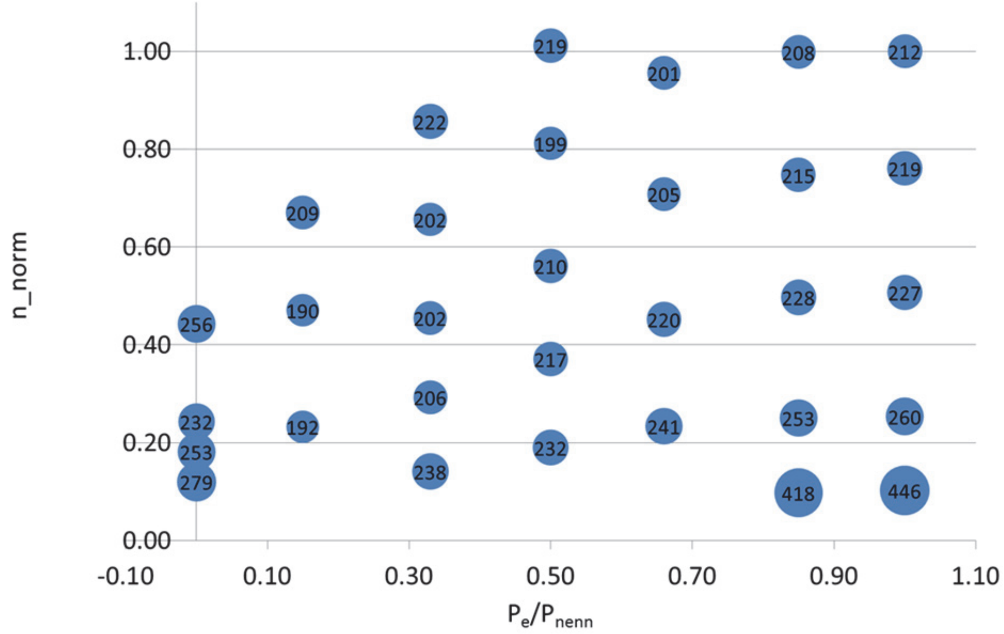
Studies were done at TU Graz on the correlation between the soot emissions and the particle mass emissions [Rexeis, 2009]. These studies yielded the following correlations for engines with or without EGR.

$$with\ EGR: \quad PM = 1.57\ x\ soot \qquad without\ EGR: \quad PM = 1.5\ x\ soot$$

These correlations were used during the data analysis to convert the soot emissions into particle mass.

In order to determine where the emissions range in comparison with the emission limits defined in the legislation, the engine output power had to be calculated for each measuring point. This was done by using fuel consumption maps of commercial engines with similar engine specifications. For the measured non-road vehicles the consumption values per second were calculated from CO_2, CO and HC by means of the Carbon balance. Together with the measurement data of the engine speed, the respective power value was calculated through interpolation from the representative fuel consumption maps.

The summation over the measurement period yielded the engine output in kWh, which is also used as the reference value in the legislation.



$$n_{Norm} = \frac{(n - n_{LL})}{(n_{Nenn} - n_{LL})}$$

Figure 4: Fuel consumption map used to calculate the engine output of the measured construction machinery (based on EURO III commercial vehicle)

This method allowed all the measured emissions to be converted to g/kWh.

Emission factors represent the emission value a vehicle emits during typical real world driving conditions. In the Handbook of Emission Factors, HBEFA speed progresses are defined for these typical real world driving conditions, which are used to determine the factors. However, there are no driving cycles that can be used to establish the emission factors for construction machinery. Therefore, typical load/engine speed cycles were defined. Average emission maps were generated from the measurements for a Stage III B wheel loader and a Stage III B excavator. These were then used to calculate the emission factors for the defined cycles. The maps were generated and the emission factors were calculated using the PHEM simulation tool.
PHEM (Passenger Car and Heavy Duty Emission Model) is a microscale emission model developed at the Institute of Internal Combustion Engines and Thermodynamics (Hausberger 2003). PHEM calculates the engine speed and power in constant time steps of 1 Hz using the backwards longitudinal dynamics approach (wheel-to-engine). FC and raw exhaust emissions are calculated from engine power and -speed considering driving resistances and transmission losses. Temperature-dependent effects in the after treatment system can be considered using an approach with its own thermal and catalytic properties.

For construction machines the engine power / engine speed progresses are directly defined as input cycles.

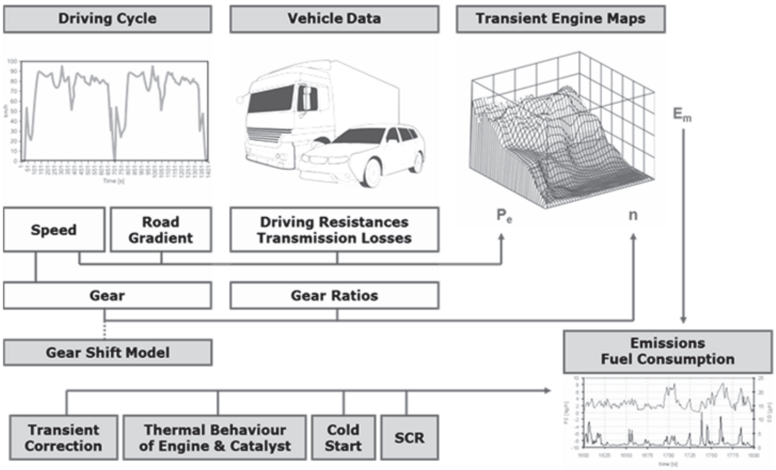


Figure 5: Microscopic emission model - PHEM

Results of Measurements

Figure 6 shows the gaseous emissions and the particle mass emissions of the wheel loaders (WL) no 1 to 4.

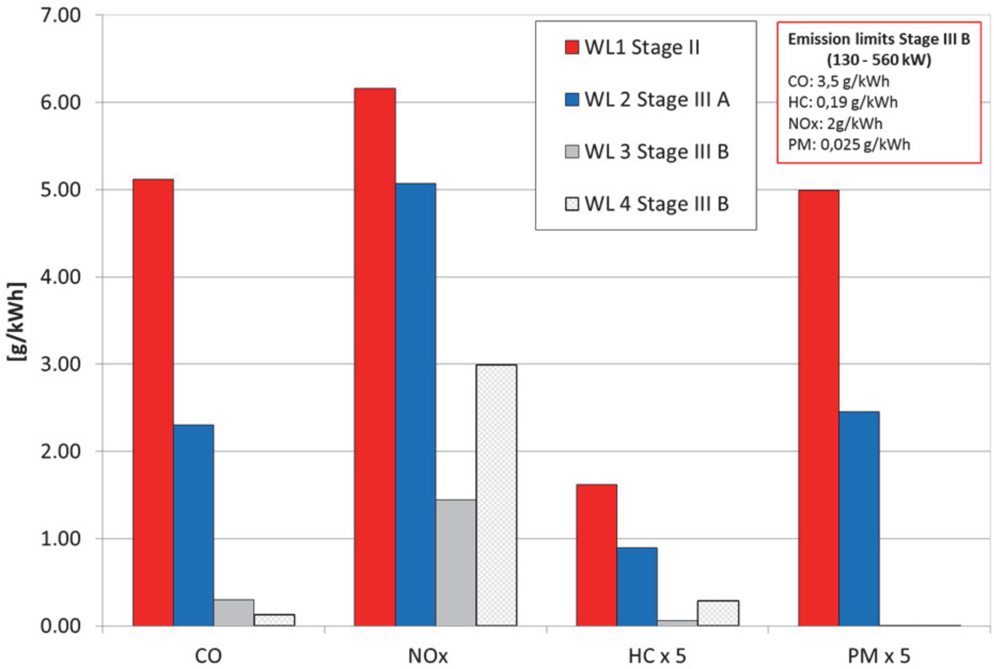


Figure 6: Emissions of wheel loaders (WL no. 1 to) in real world operation

A decrease in CO, HC, NO_x and particle mass emissions can be observed for more recent emission stages. This behavior is consistent with the decrease in emission limits. A direct comparison of emissions under real world conditions with the limits in the legislation is only partly possible because in the real world other load conditions exist than those in the approval test cycles on the engine test bed.

The two Stage III B machines achieved different emission levels of NO_x emissions. The machine with higher NO_x emissions also emitted higher NO emissions. The NO_2 value of both Stage III B machines was the same.

An examination of NO_2 emissions showed that these increased significantly for both Stage III B wheel loaders (compared with the Stage III A and Stage II machines). The reason for this increase might be the exhaust after-treatment system. NO is oxidized to NO_2 in the oxidation catalyst. This NO_2 is partly used for the regeneration of the diesel particle filter. Excess NO_2 does not take part in this reaction and can appear as direct NO_2.

The soot and particle emissions were near the detection limit due to the particle filter used for Stage III B machines.

The 7.5 ton excavator and the mini digger demonstrated similar emission behavior.

In the case of the 20 ton excavators, a Stage III B hybrid excavator was measured in addition to the conventional machines. The hybrid excavator is equipped with an electric swing motor. Electrical energy is recuperated during swing braking. The measurement setup, however, only allowed for a relatively small degree of swing, which meant that less recuperation was possible than normal. This also explains this machine's relatively high emissions. The CO emissions were the highest of all measurements, and the NO_x emissions were significantly higher than those for the second Stage III B machine.

On account of the less than optimal use pattern, the hybrid excavator had 9% higher fuel consumption values than the conventional Stage III B excavator. In real world operation, it is important to ensure optimal conditions for the hybrid system. According to the fleet operator information, reductions of up to 10% are possible. As described, however, these values could not be verified by the measurements.

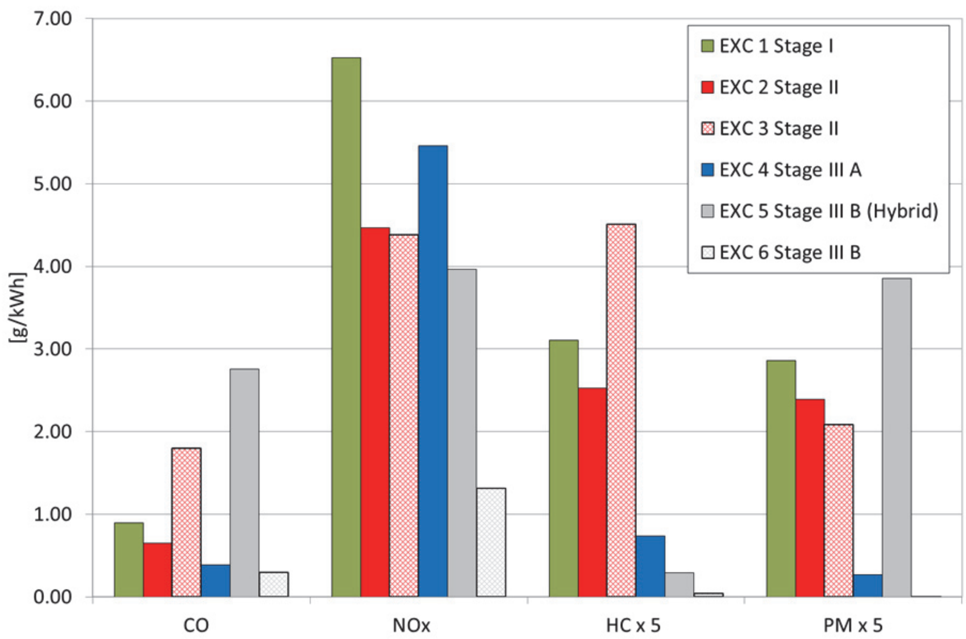


Figure 7: Emissions of 20 ton excavators (EXC no. 1 to 6) in real world operation

Generally, a decrease in CO and HC emissions to current emission stages can be observed for conventional machines without a hybrid drive. One of the Stage II machines had higher CO and HC emissions.

It was particularly noticeable that the NO_x emissions for the Stage III A machine were quite high. This was the case for all three measurement series. If the NO_x emissions are considered separately in terms of NO and NO_2, it can be observed that the NO_2 value of the Stage III A machine was in the range of the results for the Stage III B excavators.

The particle mass emissions decrease with current emission stages. Particularly in the case of the Stage III B machines with a diesel particle filter, the particle emissions are near the detection limit of the measuring equipment. The hybrid excavator is not equipped with an exhaust after-treatment system and thus had the high PM, NO_x and CO emissions

Calculation of Emission Factors

The first step was to generate emission maps for the Stage III B machines. The measurement data of the 25 ton excavator (EXC 6) and one of the wheel loaders (WL 3) were used to produce these maps. Figure 5 displays the NO_x emission map.

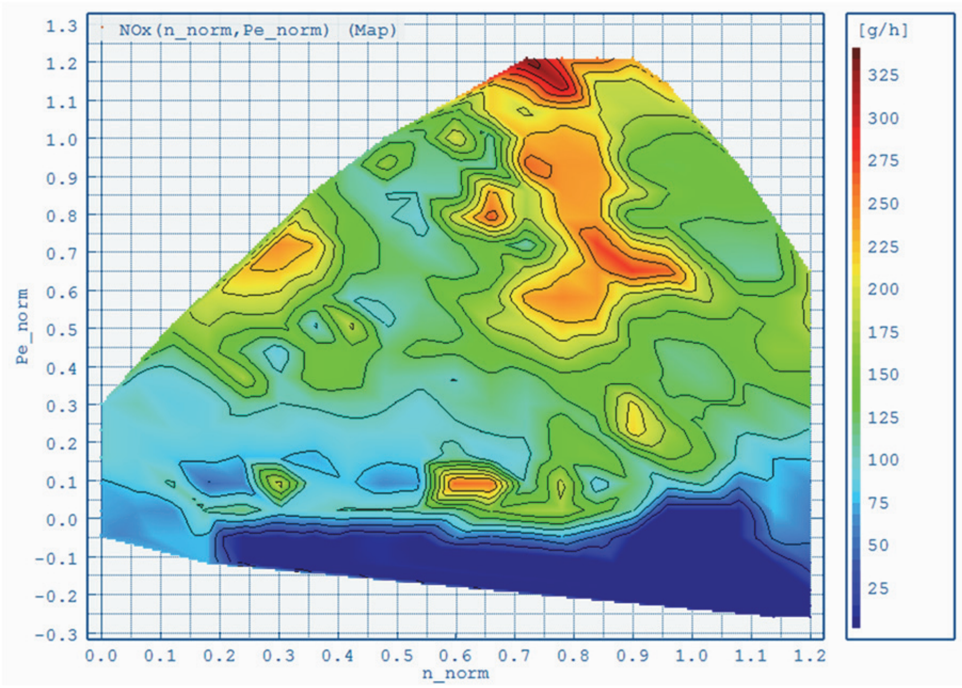


Figure 8: Stage III B NOx emission map

At next the emissions for the load and speed cycles from the wheel loader no. 3 (WL 3) measurements were calculated from the average maps. Table 2 shows a comparison of the measured emission values and the simulated emissions.

Table 2: measured and simulated emission values and derivation

Em. Comp	unit	measured	simulated		derivation
CO2	[g/h]	52564.30	52117.83		-0.8%
CO	[g/h]	20.10	18.95		-5.7%
NO	[g/h]	62.04	64.76		4.4%
NO2	[g/h]	57.03	53.80		-5.7%
NOx	[g/h]	119.07	118.44		-0.5%
HC	[g/h]	0.82	1.01		22.9%

The simulation of the emissions works quite well. The deviation was between 0.5% and 5.7%for the emission components CO_2, CO and NO_x. The derivation for the HC emissions was 23% taking into account that the HC emission value was quit low.

The next step was to define three typical power and engine speed progresses for wheel loaders. This takes place in cooperation with a wheel loader manufacturer. These operations were “loading - short driveway”, “loading - long driveway” and “mining of crushed stones”.

In order to obtain emission factors for typical use cases of wheel loaders, the emissions for these load cycles were calculated with PHEM. The emission values were added up over the duration of the cycle and the work produced by the engine was calculated. This was then used to calculate the emission factors for the particular use situation in g/kWh and in g/h.

Table 3 shows the results of the calculation.

Table 3: Emission factors for Stage III B wheel loaders in 3 typical operating conditions

	Loading short driveway	Loading long driveway	Mining
average engine power [kW]	70	100	120
CO2 [g/h]	49567.2	71933.1	93062.9
CO [g/h]	24.1	37.7	36.5
NOx [g/h]	152.1	182.4	179.4
HC [g/h]	1.4	1.8	1.8

Conclusions – Future Activity

So far, a total of 17 construction machines (excavators and wheel loaders) of varying weight classes and emission classes have been measured. This means that the individual vehicle categories are covered by at least one engine. For reliable emission data for the fleet average certainly additional measurement data is required for the individual emission classes.

Another large fleet of non-road machines are agricultural equipment. At the moment, no conclusion can be made on the emission behavior in real world operation, because no measurements have been performed. However, it can be assumed that the use of the method described above could also produce satisfactory results for this group.

Acknowledgements

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