Real Emissions of a Plant Oil Compatible Tractor Measured by PEMS and on the Tractor Test Stand

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Despite the growing interest in real operating emissions measurement and analysis of modern diesel and rapeseed oil powered tractors have been little studied. Here under real operating and ambient conditions, the emissions vary compared to the measurements on the test bench. Using a portable emissions measurement system (PEMS), TFZ has measured the emissions of a Fendt Vario 724 S4 with a Euro IV engine running on rapeseed oil fuel in accordance with DIN 51605 during ploughing in the field and on the tractor test stand.

MOTIVATION

Exhaust gas emission limits from non-road mobile machinery (NRMM) such as tractors, excavators or loaders have been increasingly tightened in recent years. Type approvals for NRMM are currently carried out on the engine test bench according to Directive 97/68/EC. For research studies, emission measurements on the entire tractor system (without removing engines) with an eddy current brake connected to the PTO have also proven effective [1-4]. Currently, there is an increased focus on real driving emissions (RDE). Under real-life operating and ambient conditions, emissions may vary compared to measurements in the laboratory [5]. RDE are usually determined by a port-

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able emission measurement system (PEMS). In contrast to heavy duty vehicles (HDV), the measurement of RDE in NRMM is not regulated by law in Europe. Investigations on NRMM and tractors show high span widths of emission values when using various evaluation methods [6-7]. First proposals of an evaluation method for NRMM based on the HDV legislation already exist [7]. A harmonised approach however to evaluate emissions for example during the cold start or the exact procedure and duration of the measurement has not been determined yet. This is due to the poor availability of data at a simultaneous high bandwidth of NRMM applications.

Besides the reduction of pollutants, combating climate change by saving greenhouse gas emissions (primarily CO_2) are important objectives for the European agricultural engineering. For current agricultural driving concepts with modern engine technology liquid biofuels are available as a climate-friendly alternative to diesel fuel [8]. Especially the use of locally produced rapeseed oil fuel according to DIN 51605 reduces greenhouse gas (GHG) emissions up to 80 % [9] and has already achieved a high level of technology in tractors [1, 3]. As for diesel fuelled tractors, there is only little knowledge about the emission behaviour of rapeseed oil fuel compatible tractors of the latest emission EU Stage IV under real-life operating conditions.

PURPOSE

The aim of this work is to investigate the emission behaviour of a rapeseed oil fuelled tractor of emission EU Stage IV during ploughing on the field and on the tractor test stand by test procedures based on the NRMM legislation. For assessing RDE of the tractor it is intended to apply the evaluation method for heavy duty vehicles (HDV). Thereby the influence of the coolant temperature at the start of evaluation and the entire duration of the measurement on the results shall be tested.

MATERIAL AND METHODS

The investigations are carried out on a plant oil compatible Fendt Vario 724 S4 of the latest emission EU Stage IV with a net engine power of 174 kW. The emission measurements are performed on the tractor test stand with diesel and rapeseed oil fuel based on the NRMM legislation and during ploughing solely with rapeseed oil fuel, **FIGURE 1** and **FIGURE 2**. Rapeseed oil fuel meets the demands of fuel standard DIN 51605. The emissions of the Deutz TCD 6.1 L6 engine are reduced by an exhaust gas aftertreatment system comprising a diesel oxidation catalyst (DOC), a diesel particle filter

FIGURE 1 Exhaust emission measurements of a Fendt 724 S4 at the tractor test stand (© TFZ)

FIGURE 2 RDE measurements of a Fendt 724 S4 with PEMS during ploughing (© TFZ)

(DPF) and a selective catalytic reduction (SCR). The fuel system is adapted for both diesel and rapeseed oil fuel operation while the engine control unit settings remain unchanged for optimised diesel operation.

On the tractor test stand of the TFZ the limited exhaust gas emission components nitrogen oxides (NO_X), carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM) are recorded by an AVL Sesam 4 gas analysis system (including FTIR, FID and PMD) and a partial flow dilution tunnel. Measurements are conducted in accordance with Directive 97/68/EC by application of a steady state test cycle (NRSC [1, 3]) and a transient test cycle with mean values aggregated over every 10 seconds of the original NRTC for type approvals on engine test benches (10sNRTC [2, 4]).

The limited emission components during ploughing are detected with a Semtech Ecostar PEMS of the company Sensors Inc. (combining NDUV, NDIR, FID, particle matter measurement and exhaust gas mass flow meter), which is mounted in a dust and water proof housing on the front linkage of the tractor. The evaluation is based on the method of the moving averaging window in line with the EU Regulations 582/2011 and 64/2012 for heavy duty vehicles (HDV legislation). Thereby monitored data of the test vehicle are divided into consecutive starting (every second) segments (windows). The length of each window corresponds to the equivalent work, performed during the reference test cycle. As reference cycle the NRTC is used. For all windows the conformity factor (CF) is generated. The CF is calculated as the ratio between the average emissions of each window (in g/kWh) and the legal emission limits of the test cycle for type approvals of NRMM. The legal emission limit values refer to the crankshaft work for measurements on the engine test bench. Since no performance data for determining the crankshaft referred work are available for rapeseed oil operation, the work performed during the test cycle is determined by the measured work at the PTO according to OECD Code 2. Due to mechanical losses and additional auxiliary components in the drive train, the cycle work referred to PTO is lower and therefore the specific emissions are about 20 % higher compared to the values based on the crankshaft work [3]. This difference is not corrected in the following. That means the outlined CF comprise limit values referred to crankshaft work and measurement data referred to PTO work.

Based on the HDV legislation the 90 % cumulative percentile of the conformity factors (CF_{90}) should not exceed the value of 1.5. In other words: 90 % of all valid averaging windows monitored during an operation period must not exceed 150 % of the legal emission limits (determined during the test cycle). Additionally according to HDV legislation the measurement does not start until a coolant temperature ($T_{CW\text{-}start}$) of 70 °C has been reached. The total work of the entire operation period considered here was 228 kWh, which is 14 times the work performed during the NRTC (16 kWh). Besides the evaluation according to the guidelines of the HDV legislation, in this study additionally measurement windows are included, where the coolant temperature ($T_{CW\text{-}Start}$) has reached at least 42 °C at start of measurement. This is done for finding out more about the influence of the cold start. Finally, the total length of the measurement period of 228 kWh was varied for the evaluation (48, 80, 112 and 144 kWh) to consider its impact on the result.

RESULTS AND DISCUSSION

During the measurement of real driving emissions of the Fendt 724 S4 with rapeseed oil fuel over nearly 3 h, ambient and operation conditions were always in compliance with guidelines and hence, all measurement windows were valid. That means that the average power of all windows was higher than 20 % of the maximum power of the tractor and altitude as well as air temperature and pressure were within the target range of the HDV legislation. Overall, there was a very low emission level during ploughing with rapeseed oil fuel. **FIGURE 3** shows the NO_X, HC and CO emissions of the PEMS measurement during ploughing with rapeseed oil fuel and at the tractor test stand during the 10sNRTC and the NRSC with both rapeseed oil and diesel fuel. All limited emission components were significantly lower than the guideline value of $CF_{90} = 1.5$ according to HDV legislation.

In all the windows the CO and HC emissions were significantly below the NRMM limits (CF = 1). The maximum conformity factors $CF_{max} = 0.25$ for HC and $CF_{max} = 0.40$ for CO demonstrate the high efficiency of the catalytic exhaust aftertreatment (EAT). Due to the particulate filter (DPF) the particulate mass (PM) was close to the detection limit with CF < 0.01. Because of the very low CO, HC and PM emissions in the field and on the tractor test stand in the following only the NO_X emissions are considered. During field work 50 % of the windows (= 50^{th} percentile) show NO_X emissions less than half (CF < 0.5) of the limits prescribed in current NRMM legislation. The mean value of NO_X during the test cycles on the tractor test stand were also below the limit (CF = 1.0). A significant difference between the use of rapeseed oil and diesel fuel cannot be recognised. Due to the low average power, the cold start phase and the transient speed and torque characteristics, emissions in 10sNRTC are higher than in the NRSC. NO_x emissions that are meas-

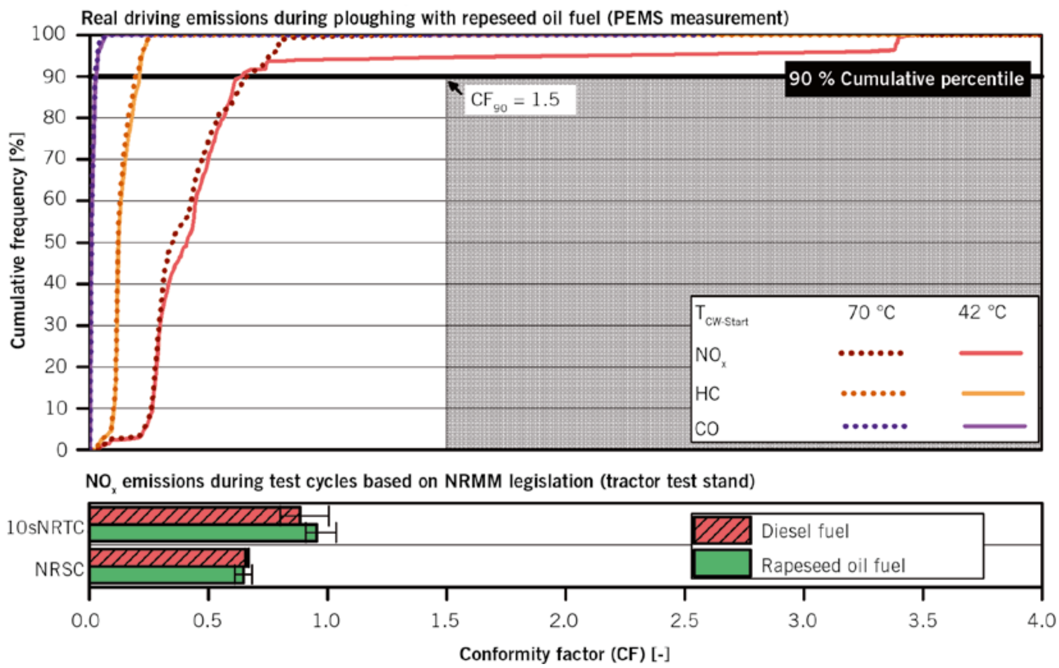

FIGURE 3 Cumulative frequency of conformity factors for NO_X, HC and CO emissions during ploughing for two ways of evaluation (starting evaluation at 70 °C or 42 °C coolant temperature ($T_{CW\text{-}Start}$)) and for NO_X applying NRTC and NRSC on the tractor test stand (© TFZ)

ured during ploughing with PEMS were in majority lower than during the NRSC and 10sNRTC at the tractor test stand. One explication is a better NO_x conversion rate by the EAT at high exhaust gas temperatures during power-demanding ploughing. Equally, in previous investigations mainly lower emission values were observed, when practice derived speed and torque characteristics of tractor work are compared with the 10sNRTC on the tractor test stand [2].

Especially at the start of measurement a connection of low coolant and exhaust gas temperatures with higher NO_X emissions is indicated. According to the HDV legislation only windows are considered where coolant temperature has firstly reached 70 °C ($T_{CW\text{-}start}$ = 70 °C) after engine start. Alternatively, in this study an evaluation is carried out, when the coolant temperature ($T_{CW\text{-}start}$) has reached 42 °C. The 9 min warm-up period from 42 °C to 70 °C coolant temperature primarily comprises the route from the farm to the field (A–B), **FIGURE 4**. Due to relatively cold exhaust gas temperatures below 250 °C within the warm-up phase, the conversion rates of catalysts are very low. Within that period, the highest NO_X emissions of more than 300 ppm were recorded. During the first ploughing furrows (B–C) the average exhaust gas temperature in the measuring windows quickly rises over 250 °C due to high engine load operation. From then on the SCR system works very efficiently, resulting in a significant reduction of NO_X below 50 ppm. Thus, CF values are under 1.0 and 0.5. Even in low load phases during turning events and on the route back to the farm (C–D), the coolant and exhaust gas temperatures remain at high level and hence the NO_X emissions are consistently low.

If solely measuring windows are included in result analysis, where coolant temperature has reached at least 70 °C ($T_{CW\text{-}start}$ = 70 °C) at the beginning of the measurement, as it is specified in HDV legislation, the period of driving to the field is disregarded. Thus, the maximum measured CF value (CF_{max}) of the NO_X emissions decreases from CF_{max} = 3.5 ($T_{CW\text{-}start}$ = 42 °C) to CF_{max} = 1.3 ($T_{CW\text{-}start}$ = 70 °C). Because of the low share of the cold start phase (about 6 %) on the total measurement time, cold start emissions have only minor effect on the 90th cumulative percentile of the CF (CF_{90}). The share of engine operating phases in the 10sNRTC with coolant temperatures below 70 °C

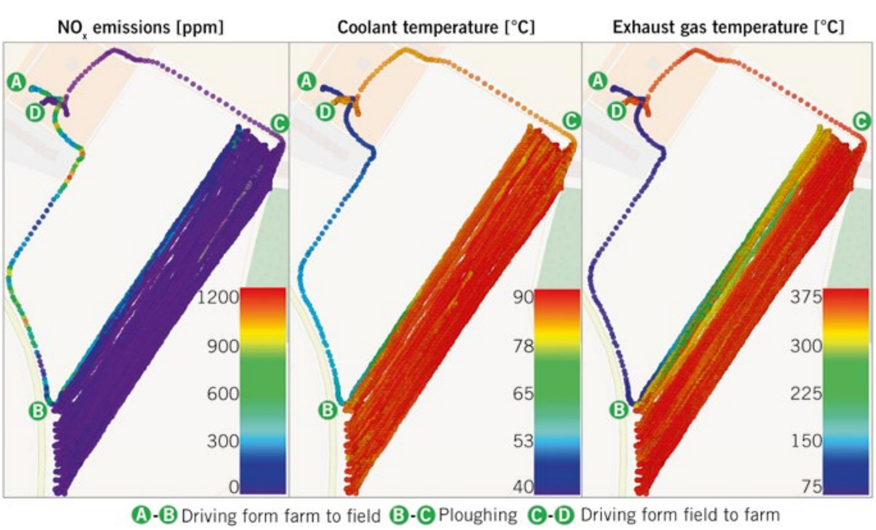

FIGURE 4 NO_X emissions, coolant and exhaust gas temperature of a rapeseed oil fuelled Fendt 724 S4 during ploughing, depending on the GPS coordinates (© TFZ)

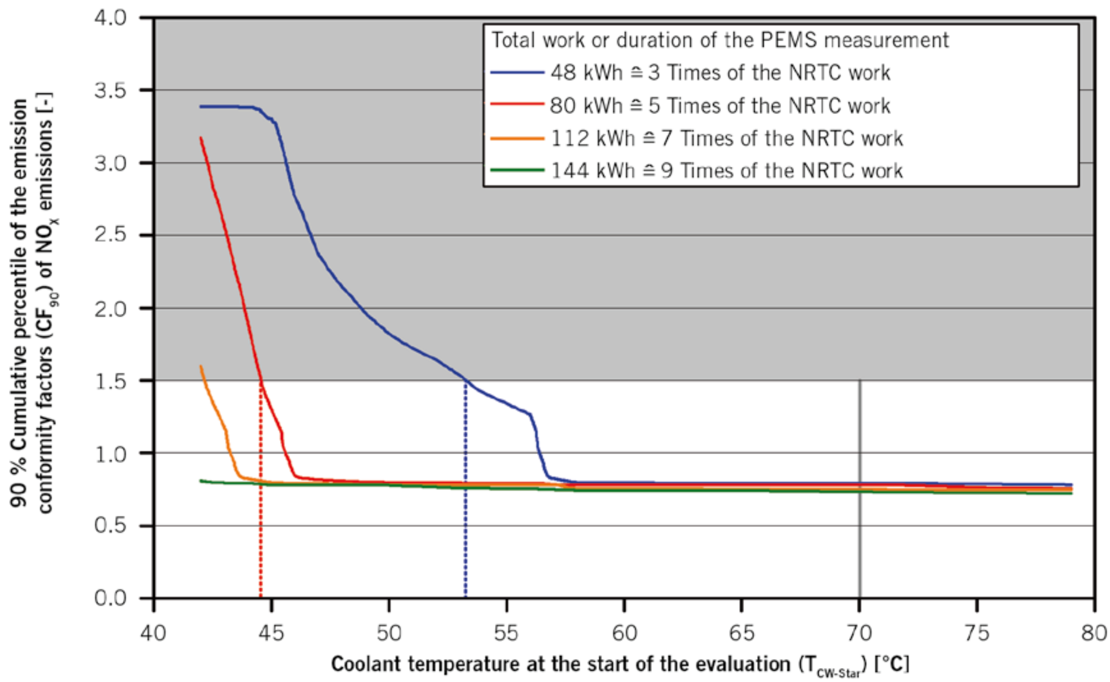

FIGURE 5 CF_{90} value of the NO_x emissions during the PEMS measurement as a function of the measurement duration and the coolant temperature at the start of the evaluation (© TFZ)

amounts 2.6 % and is therefore lower than during here presented RDE measurement (ploughing). However, other studies ascertained higher proportions (for example 11 %) of operation phases with a coolant temperature below 70 °C [3]. Further studies are needed to determine the relevant share of cold-start emissions in practice.

FIGURE 5 shows the influence of the coolant temperature at the start of the evaluation ($T_{CW\text{-}Start}$) and the total duration of measurement on the CF_{90}-value of NO_X emissions. The duration of the measurement is described as the total work (in kWh) compared to the work performed within the reference cycle (NRTC). The CF_{90} value decreases when the coolant temperature at the start of measurement ($T_{CW\text{-}Start}$) and the measurement time increases, since cold start emissions are taking greater account. With a start criterion of $T_{CW\text{-}start}$ = 70 °C, as described in the HDV legislation, the total measurement time has only very little effect on the CF_{90} value. By starting result evaluation when a coolant temperature of $T_{CW\text{-}start}$ = 53 °C or higher has been reached, the reference value of CF_{90} = 1.5 is met or undercut at each displayed measurement duration variation. Values of $CF_{90} < 1.5$ can be achieved even at lower coolant temperatures such as $T_{CW\text{-}start}$ = 44 °C, if the entire work is at minimum equal to five times the work, which is performed during the reference test cycle. This corresponds to the HDV legislation, where working time has to make up at least five times of the work of the reference cycle (> 80 kWh) for a valid measurement. Performed work beyond 5 times the work of the reference cycle however, results in marginal impact on the CF_{90} value.

CONCLUSION

With modern rapeseed oil fuelled tractors of emission EU Stage IV it is possible to fulfill relevant emission limits during measurements on a tractor test stand (NRMM legislation) as well as reference RDE values during tractor work based on the HDV legislative. Especially during ploughing high operation temperatures ensure constant high efficiency of the EAT with low emissions. RDE measured with PEMS are mainly lower than in test cycles on the tractor test stand. Thereby the emission behaviour on the tractor test stand does not differ very much between diesel and rapeseed oil fuel operation. It still has to be confirmed whether this finding also applies for real work operation. Even with PEMS only a section of the entire range of use and hence of the total emissions of the test vehicle may be considered. To classify RDE results, knowledge of the influencing factors are required. This concerns both the operating and ambient conditions as well as the method of evaluation. The interplay of cooling water and exhaust gas temperature as result of the driven load profile on the one hand and the design and the operational status of the AGN on the other hand, are important factors for the emission results.

Accordingly, the determination of the applicable conditions like engine coolant temperature at measurement start or duration of measurement has effects on the total result. To achieve a most realistic evaluation of tractor exhaust emissions further typical tractor operation profiles have to be known in order to perform representative emission measurements and derive emission factors. Equally emission-critical operating conditions can be identified, of which measures for reduction of exhaust gas emissions can be derived. Whether emissions of real driving operation can be determined by the application of practice derived actual operating profiles on the tractor test stand is currently being examined.

SUMMARY AND OUTLOOK

Despite the growing interest in RDE measurement and evaluation of modern diesel and rapeseed oil powered tractors have been only little investigated. By using a PEMS the emission behaviour of a rapeseed oil fuel compatible Fendt 724 S4, that meets latest emission EU Stage IV, is determined during ploughing in the field and during test cycles on the tractor test stand. For all measurements, the emissions of hydrocarbons (HC), carbon monoxide (CO) and particulate matter (PM) were on a very low level near the detection limit. Also nitrogen oxides (NO_X) are significantly below the limit. Due to the lack of a legal standard for NRMM, the evaluation of PEMS measurement is based on EU Regulations 582/2011 and 64/2012 for heavy duty vehicles (HDV). When the minimum working temperature of the exhaust gas aftertreatment is reached, consistently low NO_X emissions can be achieved. The choice of the point of measurement start, in dependence on the coolant temperature as well as the total measurement duration have major impacts on the results. NO_X emissions, measured in the field during ploughing were mostly lower than during the steady state (NRSC) and transient test cycle (10sNRTC) in accordance with Directive 97/68/EC on the tractor test stand. The emissions on the test stand differed only little between rapeseed oil and diesel fuel operation.

In future, more measurements of different vehicles and applications with low load (e.g. transport work) are carried out with diesel and rapeseed oil fuel. It is of further interest how to reproduce RDE measurements with the same engine speed and torque settings on the tractor test stand. Finally operation data shall show how frequently cold start phases in tractors occur in reality and what relevance this may have for the evaluation and assessment of emissions.

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