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Transient emission and fuel consumption measurements on plant oil tractors

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The evaluation of environmental impacts of agricultural machinery requires realistic test methods for the exhaust emission measurements. On the engine test bed transient cycles with fast engine speed and torque changes are state of the art. Installed tractor engines were predominantly investigated stationary at constant speed and torque using an eddy current brake on the tractor PTO shaft. Repeatable, transient emission and consumption measurements on tractors can be performed by using an adapted test cycle based on the NRTC (non-road transient cycle). The averaging of the speed and torque values in 10 second intervals (10 s NRTC) allows the implementation of dynamic test cycles on the tractor test stand despite the higher moments of inertia compared to the engine test bench, even at cold start conditions. Besides emissions and consumption, exhaust gas aftertreatment systems and thermal management of the tractor systems can be analysed and optimized. In one of the trials the averaging interval was reduced to 3 seconds (3 s NRTC). Thereby, the engine dynamic is approximated well to the original NRTC. Only during the 3 s NRTC the NO_X emissions were significantly higher compared to the 10 s NRTC and NRSC. Using rapeseed oil fuel, the emissions of particle mass (PM) were lower and the emissions of carbon monoxide (CO) and hydrocarbons (HC) as well as the specific fuel consumption were higher in the 10 s NRTC compared to the stationary NRSC (non-road steady cycle).

Keywords
Tractor, emissions, fuel consumption, test cycle, NRTC (non-road transient cycle), NRSC (non-road steady cycle), rapeseed oil, plant oill

The impact of engine exhaust gases on human and environment gains more and more importance. For this reason, the exhaust gas emissions of tractor engines were progressively restricted by legal regulations over the last years. Investigations show, that dynamic speed and load changes of diesel engines have a high impact on the emissions and fuel consumption (Bane 2012, Lindgren 2004, Blassnegger et al. 2010). The introduction of transient test cycles and the inclusion of emissions during cold start events as well as the application of portable emission measurement systems (PEMS) are measures to estimate better the real driving emission behaviour (Franco et al. 2014, Bonnel et al. 2015, Gietzelt et al. 2012). Even so, the data base for quantification of emissions caused by agricultural machinery during transient operation is still insufficient (Helms and Heidt 2014).

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The type-approval for tractor engines according to the Directives 2000/25/EC, 2005/13/EC and 97/68/EC is performed in uninstalled condition with a steady state (NRSC) and a dynamic test cycle (NRTC). For the recurrent determination of tractor engine emissions within research studies, measurements on the basis of the NRSC with the engine installed and a PTO brake have proven (Emberger et al. 2011). The NRTC was developed in the US, is mainly composed of highly transient construction machinery work test cycles (Ullman et al. 1999, Starr et al. 1999, United States Environmental Protection Agency 2003) and is primarily made for the engine test bed, like the NRSC. Higher moments of inertia caused by auxiliary units and transmission components reduce the dynamics on the tractor test stand with the power taken off at the PTO compared to the engine test bench. Landis 2012 describes an adapted NRTC variant, which can be applied on the tractor test stand with the power taken off at the PTO. The speed and torque reference values of the NRTC are averaged every ten seconds (10 s NRTC), so the dynamic is reduced and the cycle work remains unchanged. So far the 10 s NRTC has been only tested on the tractor test stand of the agricultural research centre Agroscope in Switzerland. Furthermore, it has not been researched yet, if higher dynamics than 10 s with shorter averaging intervals can be achieved and how they may affect the results of emissions and fuel consumption.

Purpose

The aim of the study is to investigate the applicability of the 10 s NRTC on the tractor test stand of the Technology and Support Centre (TFZ) in Straubing with the power taken off at the PTO. In the next step, by shorter averaging intervals a higher dynamic shall be generated compared to 10 s NRTC. In cycle validation of the measured values of speed, torque and power shall be compared with the reference values according to directive 97/68/EC. Additionally, the influence on the results of nitrogen oxides (NO_X), carbon monoxide (CO), hydrocarbons (HC), particulate matter (PM) and fuel consumption shall be evaluated using a tractor fuelled with rapeseed oil according to DIN 51605.

Approach

The NRSC (non-road steady cycle) consists of eight stationary operating points in the engine map, which are run through in a defined order. For the first four operating points the rated speed (defined by the manufacturer) is adjusted at 100 %, 75 %, 50 % and 10 % load. For the next three points the engine works at 100 %, 75 % and 50 % load at intermediate speed (which is defined as the speed where the engine has the highest torque). The last operation point of the test cycle is idle mode. The NRSC has to be performed for tractor engines of all exhaust gas stages.

In addition to the NRSC, the NRTC (non-road transient cycle) is prescribed for engines with the exhaust gas emission stages IIIB and IV. The NRTC includes fast changing operating points and is first carried out with cold start and afterwards with hot start. The limited exhaust gas emissions of the hot start cycle are weighted with 90 % and of the cold start cycle with 10 %. The NRTC starts with a 28 s and ends with a 34 s long idle section. Residual cycle parts with different dynamic speed and torque values were published by United States Environmental Protection Agency 2003 and originate of applications of a backhoe loader (29–234 s), a rubber-tire loader (235–418 s), a crawler-dozer (419–627 s), an agricultural tractor (628–777 s), an excavator (778–812 s), an arc welder (816–1019 s) and a skid steer loader (1020–1204 s).

The validation statistics of 97/68/EC is used to check the quality of the actual speed and torque control on the test bench in contrast to the required reference speed and torque values. For speed, torque and power a linear regression y = mx + b is performed using the least squares method. y are the measured and x the reference values. The slope of the regression line m, the y-intercept of the regression line b, the standard error of estimate (SE of y on x) and the coefficient of determination R^2 are the validation criteria. The comparison between the parameters of the regression line and corresponding limit values of 97/68/EC refer to the quality of the measurement. Finally, the measured actual test cycle work W_{act} is compared to the theoretical reference test cycle work W_{ref} (in kWh).

The 10 s NRTC from Landis 2012 was applied to all tractors in Table 1. In a further trial, the block by block averaging of speed and torque reference values is reduced to intervals of 5 s (5 s NRTC). Due to the use of a moving average over 3 s of the original NRTC reference values (3sNRTC) the engine dynamic is increased additionally. For the 1sNRTC the NRTC specifications are applied without averaging. The data acquisition and analysis was performed at a frequency of 1 Hz.

Table 1: Investigated tractors, test cycles, fuels and emission reduction technologies

tractor name (exhaust gas emission stage)	test cycles according to 97/68/EG	number of cylinder, fuel injection system	fuel	emission reduction technology
tractor II (II)	NRSC 10 s NRTC	6 cylinder, pump-line-nozzle	rapeseed oil fuel	internal exhaust gas recirculation
tractor IIIA (IIIA)	NRSC 10 s NRTC 3 s NRTC 1 s NRTC	4 cylinder, common-rail	diesel fuel	internal exhaust gas recirculation oxidation catalyst
tractor IIIB (IIIB)	NRSC 10 s NRTC 1 s NRTC	6 cylinder, common-rail	diesel fuel	oxidation catalyst selective catalytic reduction
tractor IV (IV)	NRSC 10 s NRTC 5 s NRTC 3 s NRTC	6 cylinder, common-rail	rapeseed oil fuel	external exhaust gas recirculation oxidation catalyst selective catalytic reduction particle filter

The cycle validation is performed for all tractors in Table 1. The effect on emissions and fuel consumption are exemplarily determined using tractor IV operated with rapeseed oil fuel according to DIN 51605 applying the 10 s NRTC, 5 s NRTC and 3 s NRTC and the NRSC. The test cycle values of emissions and fuel consumption of the NRTC test cycles are compared with the results of the NRSC.

Figure 1 shows the essential control systems and measuring instruments on the TFZ tractor test stand for consumption and emission measurements according to Directives 2000/25/EC, 97/68/EC or ISO 8178. The engine speed is controlled by a gas pedal regulator and the torque is regulated by an eddy current brake. In Emberger et al. 2013, Emberger 2013 and Thuneke et al. 2007 the set-up and procedure of the measurements of particle and gaseous exhaust emissions and fuel consumption on the tractor test stand are described.

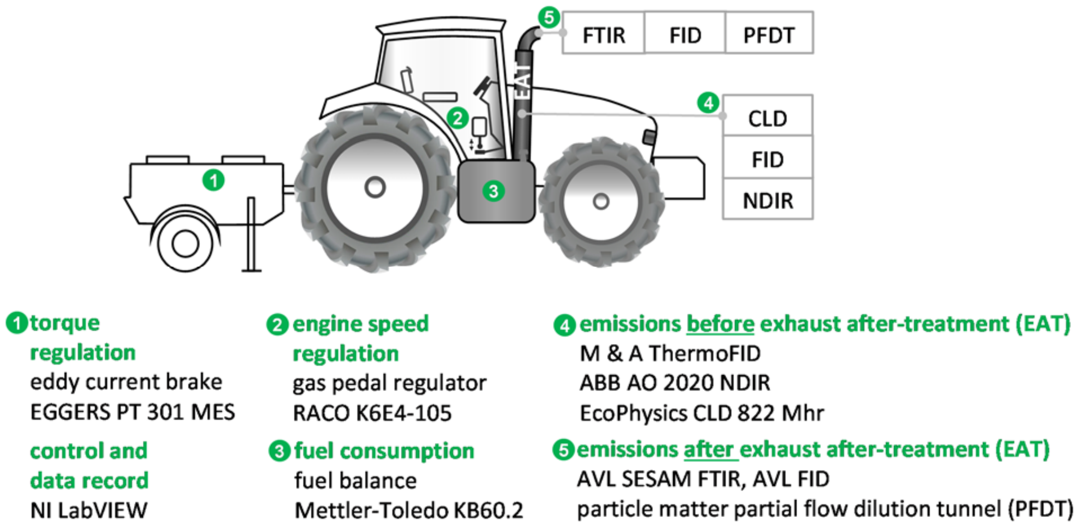

Figure 1: Important control and measurement parameters and emission analysers on the tractor test stand

The air-cooled eddy current brake showed with increasing operating temperature a declining torque value at the excitation current setting. Additionally, it has to be considered that for some tractors changing speed control strategies (as a function of the operating temperature or duration), load-dependent effects on the engine speed or mechanical inaccuracies on the accelerator pedal (hysteresis) can occur. These torque and speed deviations were detected in preliminary test runs and corrected by implementation into the control system of the gas pedal regulator and eddy current brake.

Results and discussion

Applicability of the NRTC variants on TFZ tractor test stand

Figure 2 shows the regression line parameters of validation statistics to evaluate the quality of the application of various NRTC variants on the tractor test stand.

The NRTC variants were successfully applied to several tractors with different exhaust gas emission stages at the tractor test stand. The parameters of the regression line y = mx + b of the measured and reference values (x and y) for the equivalent engine speed, engine torque and the power at PTO shaft is considerably influenced by the NRTC averaging method. Corresponding to the results of Agroscope (Landis 2012 and Landis 2014), using the 10 s NRTC the best reproducibility was achieved and the limit values of the validation statistic (97/68/EC) were met. Only for tractor II with mechanical pump-line-nozzle injection system the limits of validation of speed were not always fulfilled, due to the delayed response of the speed control in the cold start cycle. For modern tractors with common rail injection coefficients of determination (R^2) up to 99 % can be achieved for the set-actual-comparison of speed, torque and power in the 10 s NRTC. The results of 5 s NRTC with tractor IV and 3 s NRTC with tractors IIIA indicate a similar reproducibility compared to the 10 s NRTC and are within the limits of the test cycle validation. In the 3 s NRTC, dynamics increase substantially compared to the 10 s NRTC, resulting in little higher deviations of the set-actual-comparison. The required R^2 of 97 % for engine speed was missed by 2 % in the cold start cycle points, due to variations in speed of the cold engine in the first third of the 3 s NRTC. However, in the hot start cycle the requirements were achieved with a R^2 = 98 %. Without averaging the NRTC values in the 1 s NRTC, the limits of validation statistics were only fulfilled for single criteria.

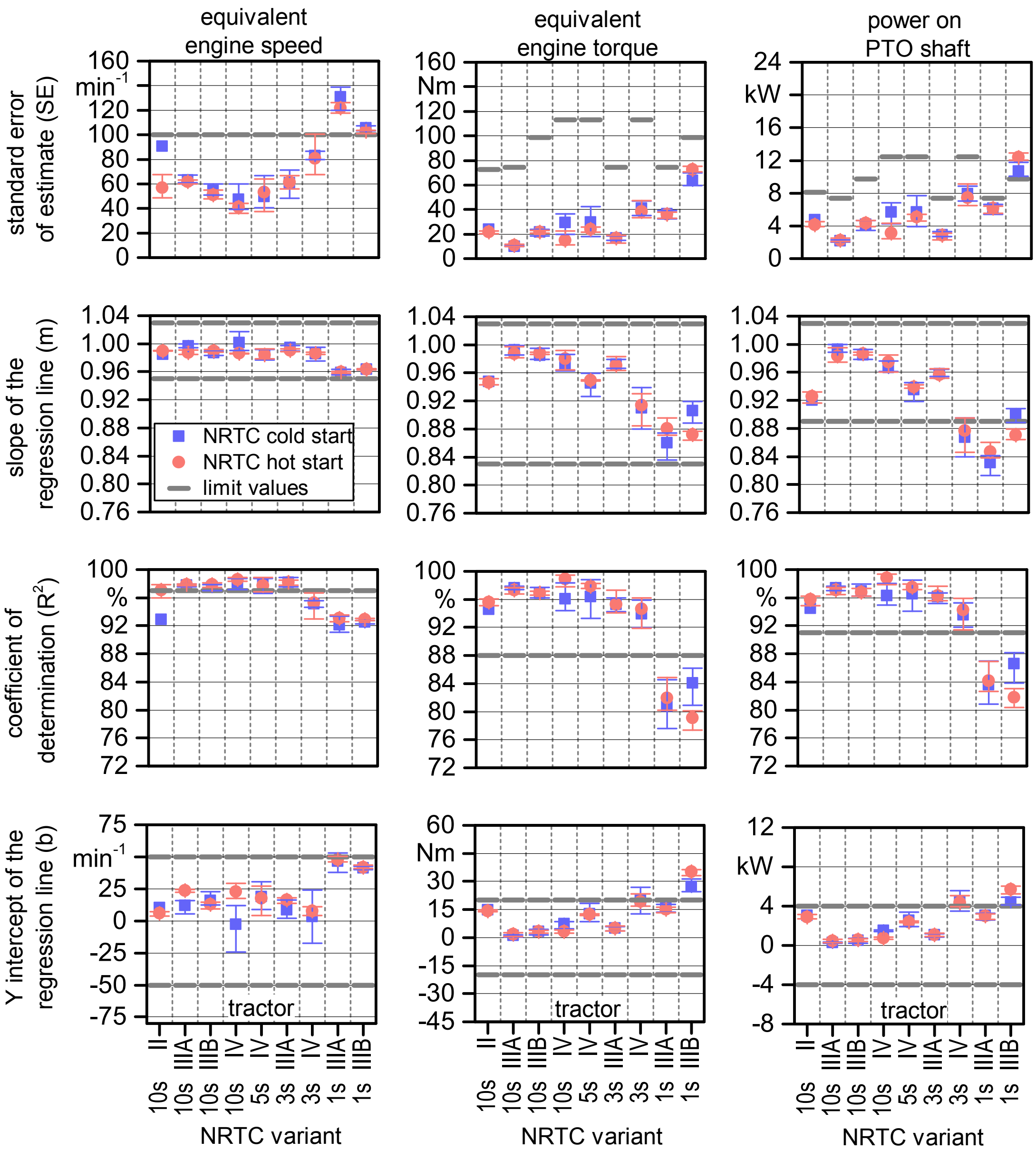

Figure 2: Average and range of the regression line parameters of actual and reference engine speed, torque and power for different NRTC variants in cold and hot start phases with three repeated test runs (n = 1 for tractor II in cold start 10 s NRTC)

Another criterion for the quality of the measurement is the difference between the actual cycle work W_{act} and the theoretical reference cycle work W_{ref}, which is for all test runs within the permitted range of –15 % to +5 % (not illustrated). For 80 % of the carried out cold and hot start test cycles

W_{act} was within ± 1 % of W_{ref}. Increasing dynamics with higher deviations of speed and torque have no impact on the average cycle work.

Figure 3 shows the reference-actual-comparison of speed and torque of the 10 s NRTC, 3 s NRTC and 1 s NRTC of tractor IIIA during the testing time on tractor test stand.

The amount of the deviations between reference and actual values of speed and torque depends on the test cycle section. By reducing the averaging interval, the deviations mainly rise in the testing time section between 150 and 600 s. This test cycle section is mainly based on rubber-tire loader and crawler-dozer works. The installed tractor engine can only follow the reference speed and torque of the 3 s NRTC and 10 s NRTC. Within the 1 s NRTC the control system of the tractor is on its limit because of the very high dynamics in some sections. Beginning from 600 s test cycle time, the engine speed remains on a higher level with lower dynamics. In some sections of the NRTC, the limits of the validation statistics are fulfilled without averaging of the NRTC reference values. Especially in the cycle section 628-777 s, which represents the operating profile of tractor engines within the NRTC, the engine operates nearly steady state.

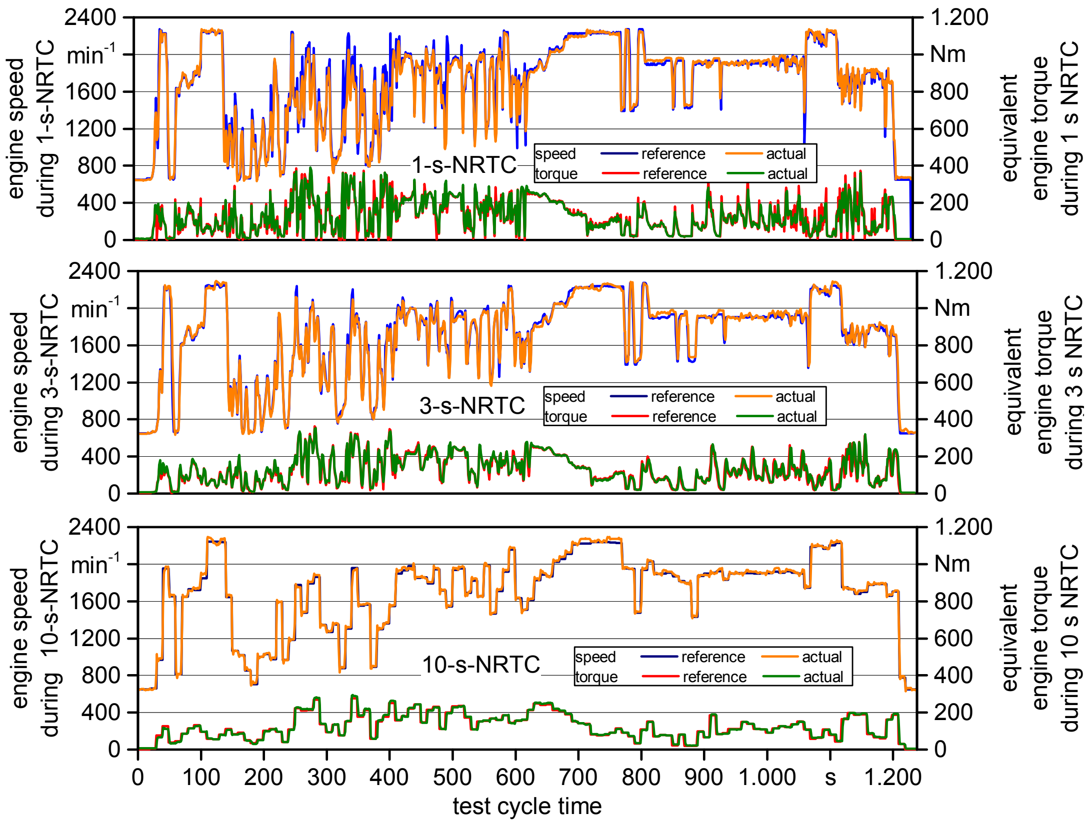

Figure 3: Reference and actual values of engine speed and torque of the NRTC variants of tractor IIIA

Emissions and fuel consumption of the 3 s NRTC, 5 s NRTC and 10 s NRTC

Figure 4 shows the effects of the NRTC variants on exhaust gas emissions and specific fuel consumption (b_e) of tractor IV in relation to the NRSC using rapeseed oil fuel. Although, for both cycles NRSC and NRTC the same limit values are valid, the exhaust emission values of the NRTC variants are partially higher (> 1) or lower (< 1) than the NRSC results.

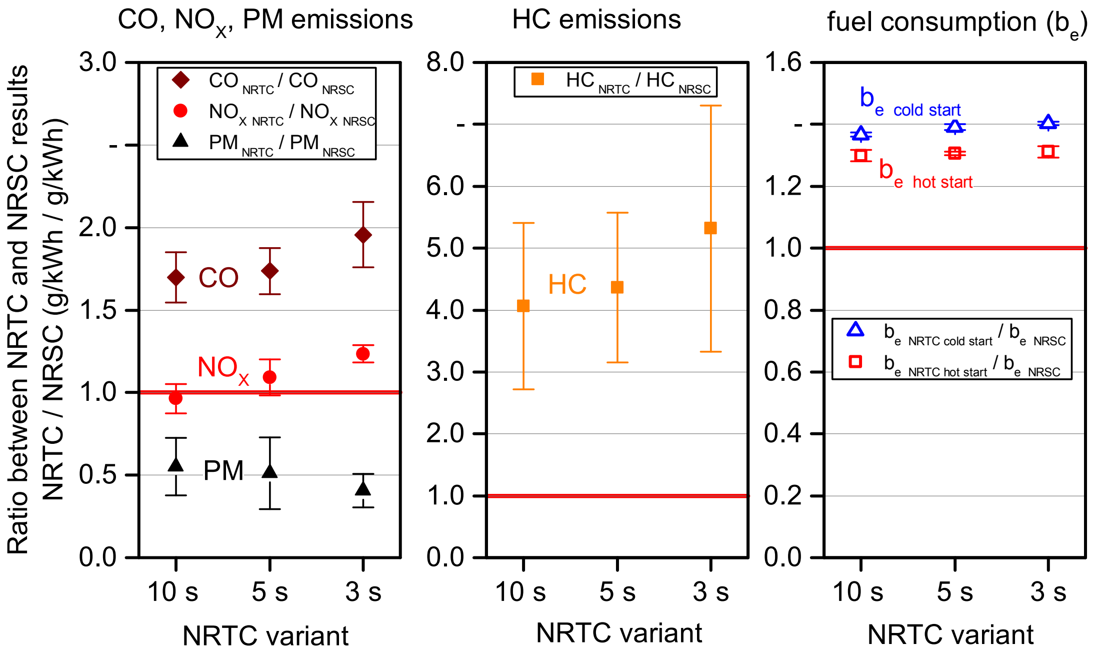

Figure 4: Average and standard deviation of the relative emission and consumption levels of different NRTC variants (n = 3) related to the NRSC results (n = 3) of tractor IV

The results of the 10 s NRTC, which were carried out on the tractor test stand of the TFZ with rapeseed oil fuel, confirm the studies of Landis 2014: Due to higher lubricating oil viscosity and the lower test cycle work of the NRTC, a higher specific fuel consumption compared to the NRSC was measured, particularly at cold start. Also, lower CO emissions in the steady state test cycle (NRSC) are in accordance with the observations of Landis 2014. An increase of the dynamic has no significant impact on the PM, HC and CO emissions. However, there is evidence of a trend towards increase in average CO and HC emissions and a reduction in average particulate emissions.

Higher standard deviations in the relative emissions are caused by the low absolute level of emissions in the NRSC of 0.05 g/kWh CO, 0.001 g/kWh HC and 0.003 g/kWh PM. These exhaust gas components are below the legal limits by far. For the cold start cycle of the 3 s NRTC and 5 s NRTC slightly higher specific fuel consumption is noticeable than in the 10 s NRTC. However, a similar amount of fuel is consumed during the hot start cycles with increasing dynamics.

The NO_X emissions increase significantly by approximately 20% for the 3 s NRTC in comparison to the NRSC and 10 s NRTC. For tractor IV, Figure 5 shows the different NO_X emissions before and after the exhaust aftertreatment (EGR and SCR catalyst) for the 3 s NRTC and 10 s NRTC over the testing time.

Higher NO_X emissions appear in the first third of the cycles. These higher NO_X emissions at the start of the cycle are caused by lower rates of exhaust gas recirculation (EGR) and low operating temperatures of the SCR catalyst. After 400 s measuring time barely any differences between hot and cold start emissions are recognizable. A comparison of the NO_X emissions of the 3 s NRTC and the 10 s NRTC shows higher NO_X emissions within the transient segments of the 3 s NRTC. The increased speed and torque dynamics affects the regulation of emission relevant engine components. A delayed control of the turbocharger or the EGR valve may lead to a worse mixture of fuel and air with partial oxygen surplus in the combustion chamber, which can enhance the NO_X formation. In general, at operating temperature the active SCR system reduces the NO_X raw emissions reliably, but a rapid increase in raw emissions can also cause an increase after the exhaust aftertreatment system. Despite many influencing factors, the emission behaviour of the tractors at the NRTC measurements on the tractor test stand was well reproducible.

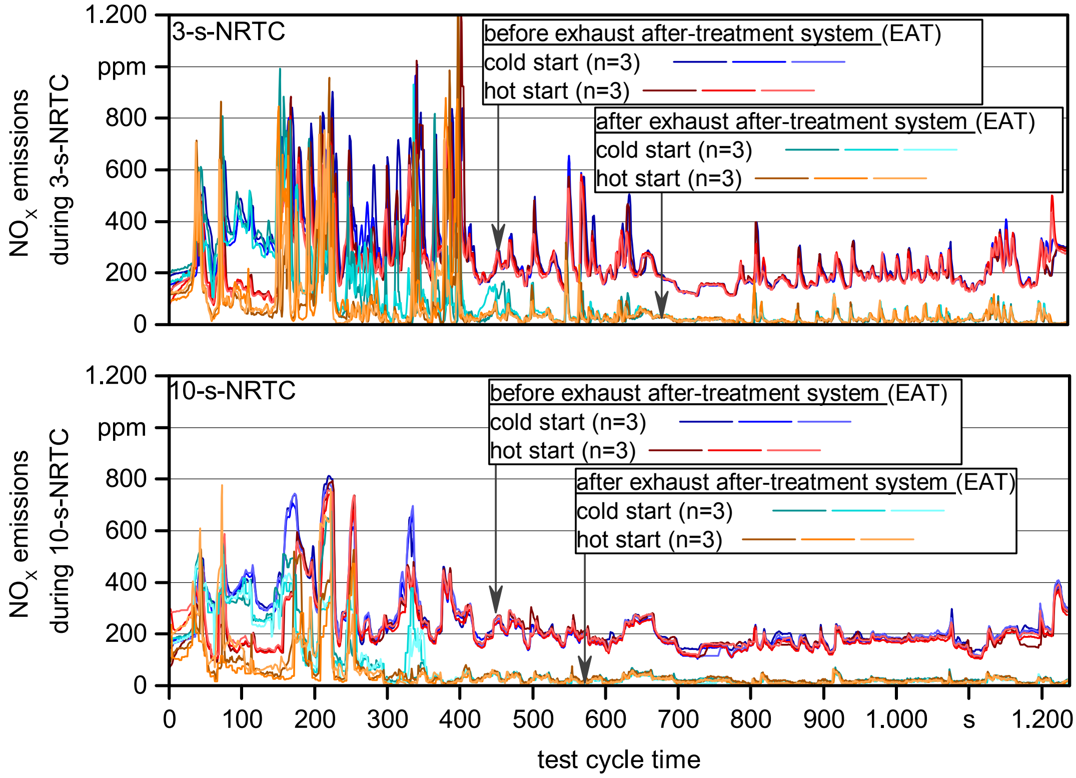

Figure 5: Nitrogen oxide (NO_X) emissions before and after the aftertreatment in cold and hot start (each with three repetitions) in 3 s NRTC and 10 s NRTC for tractor IV

Conclusions

The adapted NRTC (non-road transient cycle) variants allow exhaust emission measurements on the tractor test stand with transient engine speed and torque profiles based on the Directive 97/68/EC. The recurring determination of dynamic emission and operating characteristics of tractors, considering also the cold start, is of interest for example for long-term tractor field tests and impact assessment studies. The extensive dismounting and reassembly of the tractor engine for transient measurements on the engine test bench can be avoided.

The exhaust emission limit values according to 97/68/EC are based on the test cycle work (in kWh) at the crankshaft and are not directly comparable to the emissions related to the test cycle work at the tractor PTO shaft. By the power measurement on the tractor test stand, power losses by additional engine auxiliaries and the PTO transmission are also considered, like in real operation. Thereby, the test cycle work measured on the tractor PTO is on a lower level compared to the crankshaft and corresponds better to the real tractor operation. However, these additional components increase the moment of inertia and reduce the dynamics of speed and torque changes. Thus, averaging the original NRTC speed and torque reference values is needed for repeatable measurements on the tractor test stand. The suitability of the NRTC derived variants with averaging intervals of 10 s, 5 s, 3 s and without averaging (1 s) can vary, depending on the target of the measuring task.

The 10 s NRTC from Landis 2012 can be applied to different tractor test stands and has been tested with several tractor models. The speed, torque and power specifications are realizable on the tractor test stand in compliance with the cycle validation. By small deviations between reference and actual speed and torque values with reproducible engine work the 10 s NRTC is suitable for comparative measurements of different tractors types. Shorter averaging intervals than 10 s are less appropriate for older tractors due to the delayed response of the engine.

The 5 s NRTC and 3 s NRTC show that shorter averaging of the NRTC values for modern tractors is possible without higher deviations of speed and torque. Especially for tractors with common rail injection systems, the 3 s NRTC with higher dynamics is an alternative to the 10 s NRTC. But these results have to be confirmed by research with further tractors.

However, the approximation on the original NRTC (1 s NRTC) at tractor test stand is limited. The dynamic of the 1 s NRTC can be realized for many segments of the test cycle but with much higher deviations in speed and torque. Application of the 1 s NRTC without averaging results in higher deviations of the set-actual-comparison, but as a worst-case-test it allows better statements about the emission behaviour during very dynamic engine operation. Due to some parts of the 1 s NRTC can be realized without averaging, it could be also possible to change the averaging interval in dependence on the time segments of the test cycle.

For the researched tractor the emission behaviour during the 10 s NRTC, 5 s NRTC and 3 s NRTC differs partially considerably from that during the NRSC. Within the NRTC variants only the fuel consumption at cold start and the NO_X emissions are significantly rising with increasing dynamic from the 3 s NRTC to the 10 s NRTC. Thereby for most emission components and the fuel consumption the differences within NRTC variants are lower than the difference compared to the NRSC. Thus, despite the comparatively low dynamic, the 10 s NRTC allows the estimation of the emission behaviour at dynamic operation and compared to the NRSC.

In future, further tractors should be researched, also concerning unlimited exhaust gas components (e. g. particle number). Furthermore it is of interest, how speed and torque profiles of real tractor work affects emissions and consumption in comparison to the NRSC and NRTC variants.

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