

## Modelling of Non-Road Transient Cycle – Comparison of Three Tractors

### Modelování non-road transient cycle – porovnání 3 traktorů

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#### Abstract

The paper describes the modeling of NRTC (Non-Road Transient Cycle) test procedure based on previously measured characteristics of fuel consumption, carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), hydrocarbons (HC), nitrogen oxides (NO<sub>x</sub>) and particulates (PM) production. It makes possible to compare the current technical condition of an internal combustion engine of an agricultural tractor with its previous state or other tractor's engine. Based on measured characteristics, it is also possible to model any other cycle without further measurements (NRSC test procedure, cycle for specific conditions – mountain tractor, etc.). The result may thus contribute to improving the environment by reducing the production of harmful substances emitted into the air and save money due to reduced fuel consumption.

**Keywords:** NRTC test procedure, fuel consumption, emission characteristics

#### Abstrakt

Příspěvek popisuje možnost modelování testu NRTC (Non-Road Transient Cycle) na základě změřených charakteristik spotřeby paliva, oxidu uhelnatého (CO), oxidu uhličitého (CO<sub>2</sub>), nespálených uhlovodíků (HC), oxidů dusíku (NO<sub>x</sub>) a pevných částic (PM). Ve srovnání s předchozím zjištěným technickým stavem lze stanovit změny technického stavu spalovacích motorů zemědělských nebo lesnických traktorů. Současně však lze na základě změřených veličinových charakteristik porovnat mezi sebou libovolné traktory a také modelovat libovolný jiný cyklus bez dalšího měření (NRSC test, cyklus pro specifické podmínky – horský traktor apod.). Ve výsledku lze tak přispět ke zlepšení životního prostředí snížením produkce škodlivých látek vypouštěných do ovzduší a současně uspořit peníze sníženou spotřebou paliva.

**Klíčová slova:** NRTC test, spotřeba paliva, emisní charakteristiky

## Introduction

During operations of agricultural and forestry tractors, which are mainly driven by diesel engines, large quantities of gaseous emissions and particulate emissions are released from the exhaust pipe into the air. These are mainly carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), hydrocarbons (HC), nitrogen oxides (NO<sub>x</sub>) and particulates (PM). Due to the negative impact of these emissions on the environment, it has proved necessary to limit legislatively the amount of pollutants produced by the engine (Brožová and Růžička, 2009). Therefore, all tractors placed on the EU market have to comply with all regulations concerning the production of harmful emissions. European emission regulations for agricultural and forestry tractors are similar to the known EURO regulations for cars and trucks. Because of a different nature of tractor engine work, emission limits and methods of loading the engine during the certification measurements vary.

Currently applicable rules are based on Directive 97/68/EC and its associated Directives 2004/26/EC, 2000/25/EC and 2005/13/EC. These directives bring a gradual tightening of emission limits for agricultural and forestry tractors in several stages (Table 1) in the years of 2001–2014 (Bauer et al., 2006).

The above-mentioned directives concede two test procedures, which can be used during the emission type approval for agricultural and forestry tractors. The older test procedure, which is called NRSC (Non-Road Steady Cycle), represents the measurement of emission parameters of the engine at steady state. This test procedure is also often known as eight-mode cycle because it prescribes testing the engine in eight different modes. Newer NRTC test procedure (Non-Road Transient Cycle) serves to measure the engine in transient mode where speed and load changes throughout the cycle. The waveform of this cycle was designed so that it closely matches the real work of the engine during the normal operation of the tractor.

Table 1: European emission limits for engines of agricultural and forestry tractors – NRTC ( $\text{g}\cdot\text{kWh}^{-1}$ ) (Bauer et al., 2006)

Net power	Emission component	Period of validity							
		2006	2007	2010	2011	2012	2013	2014	20??
37–56	CO		5.0			5.0			
	HC		-			-			
	NO <sub>x</sub>		-			-			
	NO <sub>x</sub> + HC		4.7			4.7			
	PM		0.4			0.025			
56–75	CO		5.0		5.0			5.0	
	HC		-		0.19			0.19	
	NO <sub>x</sub>		-		3.3			0.4	
	NO <sub>x</sub> + HC		4.7		-			-	
	PM		0.4		0.025			0.025	
75–130	CO	5.0			5.0			5.0	
	HC	-			0.19			0.19	
	NO <sub>x</sub>	-			3.3			0.4	
	NO <sub>x</sub> + HC	4.0			-			-	
	PM	0.3			0.025			0.025	
More than 130	CO	3.5		3.5			3.5		
	HC	-		0.19			0.19		
	NO <sub>x</sub>	-		2.0			0.4		
	NO <sub>x</sub> + HC	4.0		-			-		
	PM	0.2		0.025			0.025		
		stage IIIA		stage IIIB			stage IV		

The above directives prescribe for agricultural and forestry tractors the following use of these test procedures in different stages:

- NRSC test procedure can be used to issue approval for all monitored components in stages I, II and III, in stage IIIB and IV, it can only be used for measurement of gaseous emissions (CO, HC, NO<sub>x</sub>);
- NRTC test should be used for measurement of particulate emissions (PM) in stage IIIB and IV, it can also be used for issuing of approval in stage IIIA and measurement of gaseous pollutants (CO, HC, NO<sub>x</sub>) in stage IIIB and IV.

Emission approval guarantees that any new tractor put into operation does not exceed emission limits. However, using the tractor as well as any other machinery is connected with the wear of all its parts including the engine. This leads to a gradual increase in fuel consumption along with an increased production of emissions. To determine the extent of degradation of emission characteristics of the tractor during its normal operation is difficult, even though each tractor has to go through periodic emission tests. These control measurements, due to the requirement for a low price, can detect only tractors with a significant increase in the production of solid particles because they measure only the smoke opacity of diesel engine using a free acceleration test procedure.

If, however, there are available current emission surfaces [dependence of emissions on engine speed and torque (Pexa et al., 2010)] for the tractor, these surfaces can be used not only to model emissions for the specific job of the tractor but also for modelling of homologation tests. Given that the used emission surfaces are made up of points measured in the stationary regime of the engine, the values calculated by modelling of NRTC test cannot be directly compared with emission limits. However, there are potentials to use the results of model calculations to evaluate the actual technical condition of the tractor and to compare different tractors (Hromádko et al., 2008; Kadleček et al., 2009).

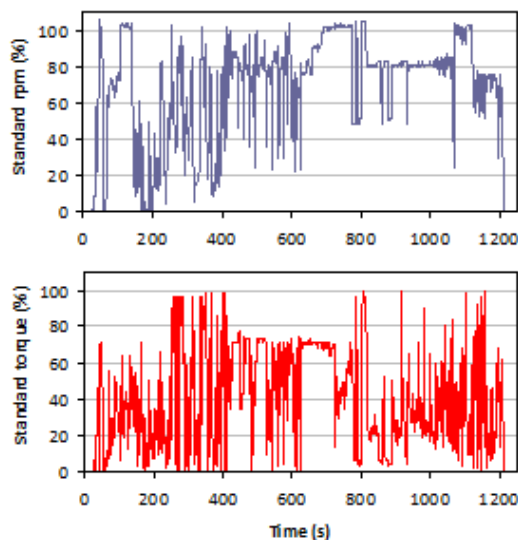


Figure 1: NRTC test procedure – normalised engine speed  $N$  (%) and normalised engine torque  $M_n$  (%) in individual measuring points

In this paper, NRTC test procedures (Fig. 1) are modelled for the tractors Zetor Forterra 8641 (Fig. 2a), Case IH JX90 (Fig. 2b.) and Fendt Farmer 412 Vario (Fig. 2c).

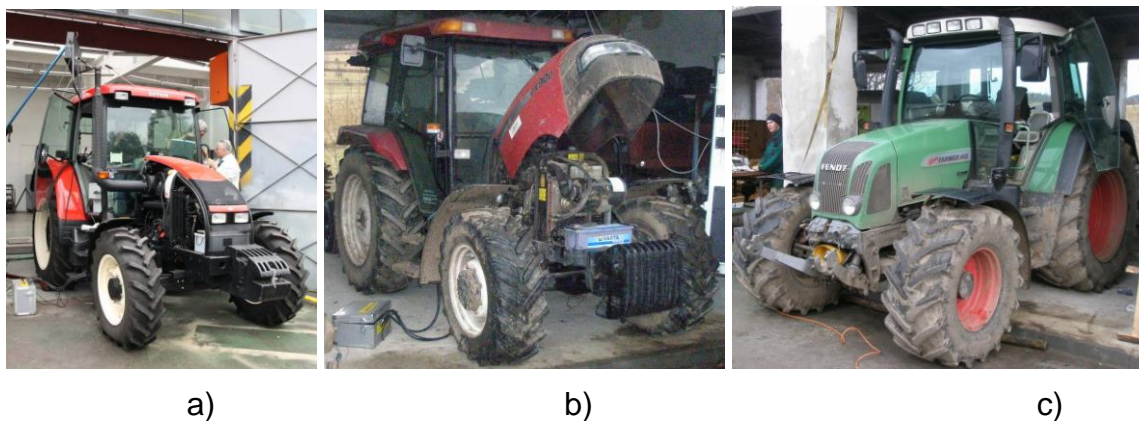


Figure 2: Measured tractors: a) Zetor Forterra 8641 – max. power 61 kW, max. torque 353 Nm, b) Case IH JX 90 – max. power 80 kW, max. torque 382 Nm, c) Fendt Farmer 412 Vario – max. power 93 kW, max. torque 622 Nm

## Materials and Methods

### Measuring equipment

Measuring apparatuses were gradually attached the measured tractor Zetor Forterra 8641, Case IH JX 90 and Fendt Farmer 412 Vario. The crucial part was a weighting hydraulic dynamometer connected to tractor by rear power take-off, the nominal speed of which was  $540 \text{ min}^{-1}$  (Figure 3a). The basic parameters of the used dynamometer AW NEB 400 are shown in Table 2.

Table 2: Basic parameters of AW NEB 400 dynamometer

Maximal PTO torque [Nm]	2850
Maximal PTO speed [ $\text{min}^{-1}$ ]	3200
Maximal breaking power [kW]	343
Maximal breaking power at PTO speed $540 \text{ min}^{-1}$ [kW]	149
Maximal breaking power at PTO speed $1000 \text{ min}^{-1}$ [kW]	298
Measurement error [%]	2
Weight of the dynamometer without water for cooling [kg]	586
Cooling water tank capacity [l]	370

For the measurement of fuel consumption, there was used a fuel box (fuel consumption indicator), which consists of two flow indicators Macnaught MSeries FlowMeter M2ASP-1R. One fuel consumption indicator measures the quantity of fuel delivered to the engine, and the second one measures the fuel quantity which flows back to the tank (Figure 3b). The main parameters of the flow indicator M2ASP-1R are shown in Table 3.

Table 3: The main parameters of the M2ASP-1R flow indicator

Maximal flow rate [ $\text{l} \cdot \text{h}^{-1}$ ]	500
Resolution [ $\text{puls} \cdot \text{l}^{-1}$ ]	400
Measurement error [%]	1

Emissions were measured by a combination of three apparatuses (Figure 3c), the most important of which was the analyser Atal AT 505 (CO, CO<sub>2</sub>, HC, O<sub>2</sub>, air temperature). Another apparatus was Atal AT 600, which measured the smokiness and temperature of diesel. The last one was Asin FG34, measuring NO and as the control CO, CO<sub>2</sub>, O<sub>2</sub>.

Table 4: Basic parameters of emissions analysers

<b>Atal AT 505</b>		
Component	Resolution	Accuracy
CO	0.01 % vol.	0.03 % vol. or 5 % read value
CO <sub>2</sub>	0.1 % vol.	0.5 % vol. or 5 % read value
HC	1 ppm vol.	10 ppm vol. or 5 % read value
O <sub>2</sub>	0.01 % vol.	0.1 % vol. or 5 % read value
Temperature	1 °C	2 °C (read value)
<b>Atal AT 600</b>		
Component	Resolution	Accuracy
Opacity	0.1 %	2 %
Temperature	1 °C	2 °C
<b>Asin FG34</b>		
Component	Resolution	Range (overload)
NO	1 ppm	1000 ppm (4000 ppm)

In order to convert the values measured by analysers from percentage into mass units, there was used a lossless nozzle for the measurement of suction air quantity.

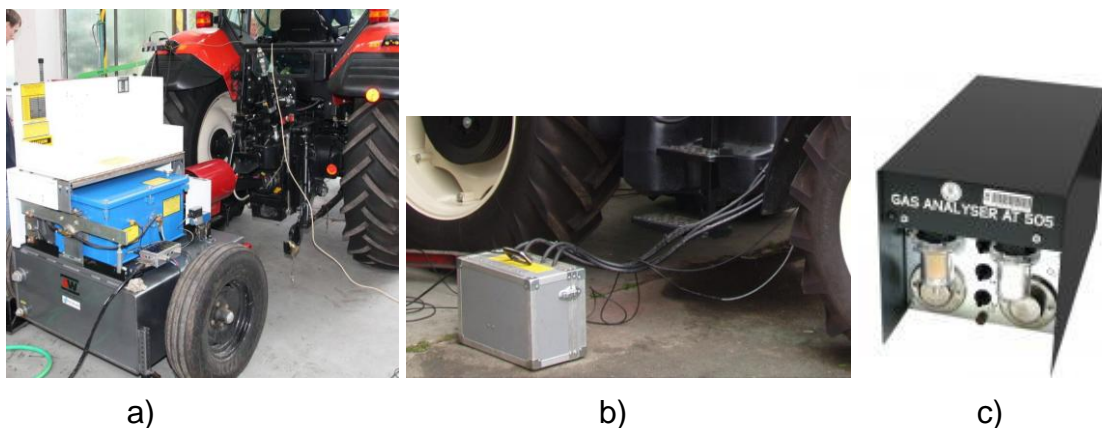


Figure 3: Measuring devices: a) Dynamometer AW NEB 400, b) Fuel consumption indicator Macnaught MSeries FlowMeter M2ASP-1R, c) Emission analyser Atal AT 505

### NRTC test

The NRTC test procedure represents the testing of the engine in transient conditions when engine speed and its torque are changing in each second of the test. The total length of the test is 1238 seconds. The directive gives the program for the dynamometer which represents a sequence of so-called normalised speed and normalised torque of the engine (Figure 1). These values must be converted to a reference test cycle on the basis of a mapping curve (engine torque curve measured at a full load of the engine), called denormalisation of the engine speed and engine torque.

### Generation of the reference test cycle

While we are generating the reference test cycle, the reference engine speed is determined first. This speed represents 100 % of normalised speed values in the program for the dynamometer. The reference speed is determined by Eq. (1).

$$n_{ref} = n_n + 0.95 \cdot (n_v - n_n) \quad (1)$$

where:

$n_{ref}$  – reference engine speed [ $1\text{min}^{-1}$ ]

$n_v$  – high engine speed (the highest engine speed where 70 % of rated power is delivered) [ $1\text{min}^{-1}$ ]

$n_n$  – low engine speed (the lowest engine speed where 50 % of rated power is delivered) [ $1\text{min}^{-1}$ ]

### Denormalisation of engine speed and torque

Actual engine speed at different points within the test cycle is determined by means of Eq. (2).

$$n_{sk} = \frac{n_{norm} \cdot n_{ref} - n_{vol}}{100} + n_{vol} \quad (2)$$

where:

$n_{sk}$  – actual engine speed at a given point of the test cycle [ $1\text{min}^{-1}$ ]

$n_{norm}$  – normalised engine speed at a given point of the test cycle [%]

$n_{vol}$  – engine idle speed [ $1\text{min}^{-1}$ ]

Actual engine torque at different points within the test cycle is determined by means of Eq. (3).

$$M_{sk} = \frac{M_{norm} \cdot M_{max}}{100} \quad (3)$$

where:

$M_{sk}$  – actual engine torque at a given point of the test cycle [Nm]

$M_{norm}$  – normalised engine torque at a given point of the test cycle [%]

$M_{max}$  – maximal engine torque at a given engine speed [Nm]

Twenty-five measuring points and four checkpoints (Fig. 4a) were chosen to create consumption and emissions surfaces. These points were interpolated with the software MathCad 2001 Professional, using an appropriate function. The function REGRESS creates a matrix of 1681 points and it allows you to choose the degree of the polynomial. The function SPLINE creates a continuous surface for computing driving regimes from the previously created matrix of 1681 points. All surfaces are limited by a full-load characteristic of the engine (Hromádko et al., 2007). The dot matrixes with 41 rows and 41 columns (1681 points) were created for further computer processing (Fig. 4b) from above surfaces. Examples of the resulting matrix are shown in a contour graph in Fig. 5.

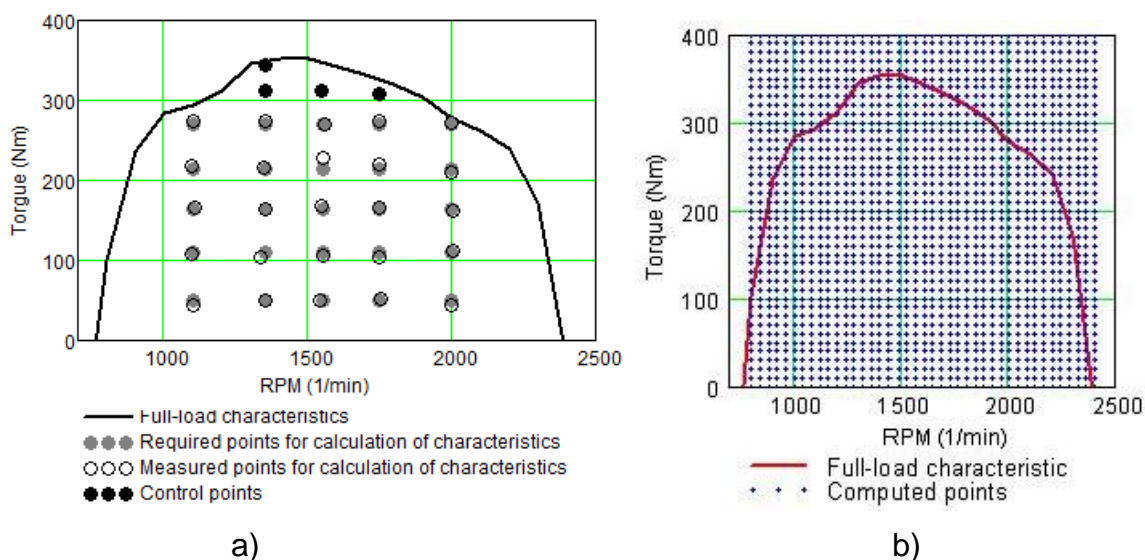


Figure 4: Points for determining surfaces: a) measured, b) calculated



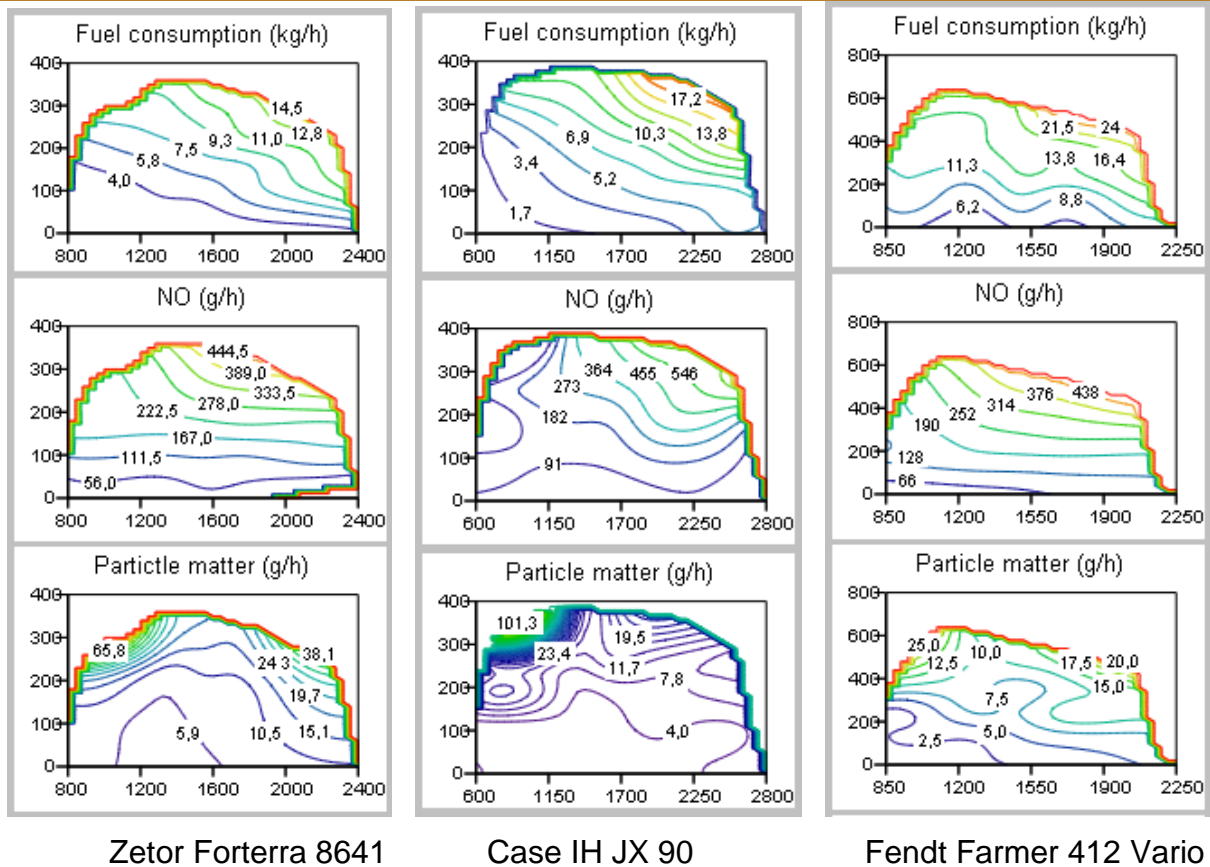


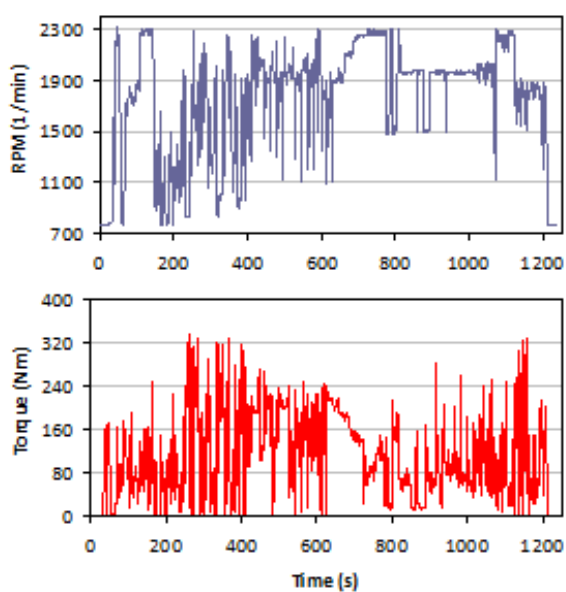
Figure 5: Surfaces of fuel consumption, nitrogen monoxide emission (NO) and particulates emission (PM): x-axis represents engine speed [ $1 \cdot \text{min}^{-1}$ ], y-axis represent engine torque [Nm]

## Results

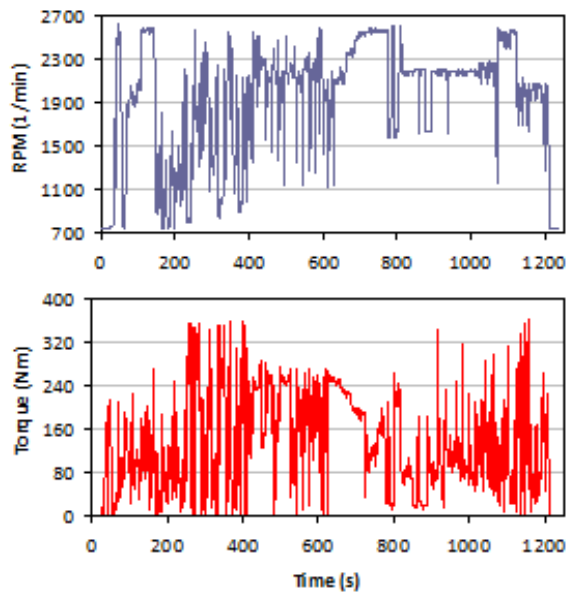
Actual engine speed and torque are determined based on Eq. 2 and 3 at all the points of NRTC test. Denormalised engine speed and torque are shown in Fig. 6 for all the three tractors.

The values of fuel consumption and emission production are determined for each test point for individual tractor (Fig. 6) based on previously measured and calculated surfaces of fuel consumption and emission production (Fig. 5). The fuel consumption and emissions production of the entire test cycle is obtained by the sum of values provided for individual points. The results are shown in Table 5 for the tractor Zetor Forterra 8641, in Table 6 for the tractor Case IH JX 90 and in Table 7 for the tractor Fendt Farmer 412 Vario. The grey-shaded values indicate that the calculated emission production exceeds the regulations being in force since 2011 when it is mandatory to use the NRTC test. It is arguable that all three tractors meet two of the monitored values (CO and HC) and do not meet other two of the monitored values ( $\text{NO}_x$  and PM). This comparison of the three tractors should be seen only as a model comparison because each of the three tractors was manufactured in a different year and so each of them has to fulfil different regulations. The other fact is that comparison with limits is only approximate because calculated values do not reflect the influence of unsteady regime of the engine. Regardless of these problems, the

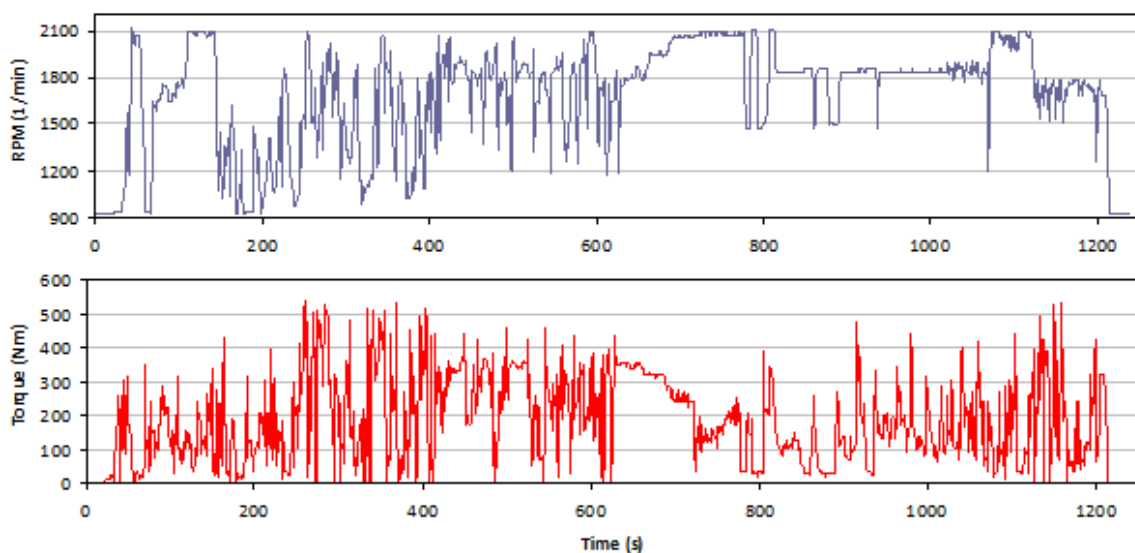
comparison of tractors using the above methodology can determine the best and the worst tractor of them from the point of fuel consumption and emissions production.



a) Zetor Forterra 8641



b) Case IH JX 90



c) Fendt Farmer 412 Vario

Figure 6: Denormalised engine speed  $N_i$  [ $1 \cdot \text{min}^{-1}$ ] and denormalised engine torque  $M_{Ti}$  [Nm] for NRTC test: a) Zetor Forterra 8641, b) Case IH JX 90, c) Fendt Farmer 412 Vario

Table 5: Resulting values of NRTC test – Zetor Forterra 8641

Quantity	Weighted average of quantity [ $g \cdot h^{-1}$ ]	Weighted average of engine power [kW]	Weighted average of specific quantity [ $g \cdot kWh^{-1}$ ]	Total sum for the whole test [g]
Fuel consumption	7210	21.4	337	2480
CO	47.1		2.2	16.2
CO <sub>2</sub>	27700		1290	9510
NO <sub>x</sub>	171		7.99	58.8
HC	1.85		0.086	0.64
PM	12.6		0.59	4.33

Table 6: Resulting values of NRTC test – Case IH JX 90

Quantity	Weighted average of quantity [ $g \cdot h^{-1}$ ]	Weighted average of engine power [kW]	Weighted average of specific quantity [ $g \cdot kWh^{-1}$ ]	Total sum for the whole test [g]
Fuel consumption	7480	28.6	262	2570
CO	52.2		1.82	17.9
CO <sub>2</sub>	32800		1150	11300
NO <sub>x</sub>	239		8.36	82.3
HC	0.64		0.022	0.22
PM	5.72		0.2	1.97

Table 7: Resulting values of NRTC test – Fendt Farmer 412 Vario

Quantity	Weighted average of quantity [ $g \cdot h^{-1}$ ]	Weighted average of engine power [kW]	Weighted average of specific quantity [ $g \cdot kWh^{-1}$ ]	Total sum for the whole test [g]
Fuel consumption	11900	34.2	348	4070
CO	46.8		1.37	16.1
CO <sub>2</sub>	41400		1210	14200
NO <sub>x</sub>	191		5.58	65.6
HC	0.65		0.019	0.22
PM	7.27		0.21	2.5

There is a reciprocal comparison of the measured tractors in Fig. 7. From this comparison, it is evident that the tractor Case IH JX 90 reached the best results for

CO<sub>2</sub> emission (hence also fuel consumption) and PM. The tractor Fendt Farmer 412 Vario reached the best results for CO, HC and NO<sub>x</sub> emissions components. The tractor Zetor Forterra 8641 reached the worst results for CO<sub>2</sub>, HC and PM emission production, the tractor Fendt Farmer 412 Vario reached the worst results for fuel consumption and the tractor Case IH JX 90 reached the worst results for NO<sub>x</sub> production. Zetor Forterra 8641 is the best in fuel consumption, CO, CO<sub>2</sub> and NO<sub>x</sub> production in terms of total production for the whole NRTC test. Case IH JX 90 dominated the remaining two components of emissions (HC and PM).

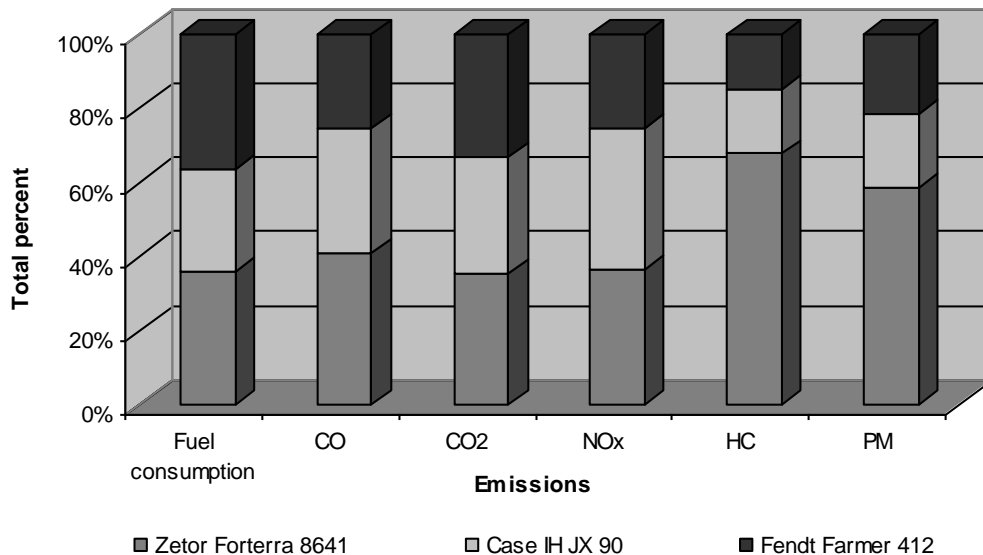


Figure 7: Reciprocal comparison of NRTC test results for measured tractors

## Discussion and Conclusion

NRTC test modelling is feasible and provides a quick comparison of selected tractors, provided that there are known the surfaces of fuel consumption and emission production. If an agricultural company considers which tractor to choose from the market, this method allows identifying the best tractor on the basis of comparison with simulated NRTC test.

The advantage of the modelled cycle is the achievement of the same result and 100 % repeatability which are guaranteed for repeated simulations for given engine characteristics. The main disadvantage is that the engine characteristics are determined by a static method and so the dynamic run of the NRTC test may involve a mistake, especially in transitional domains. It would be therefore better to obtain these characteristics using dynamic methods.

This method is sufficient for service and maintenance when in particular the technical condition of the tractor and its development is assessed. The difference between a dynamic and static surface leads to a systematic error which causes the achievement of lower final values in the test. This does no harm because the authors assume that the static application of NRTC test reflects the work of the machine better than the NRSC test (8 measurement points) and it is thus possible to quickly notice a significant change in the technical condition of the tractor. The paper demonstrates the comparison of three tractors using the NRTC test which is modelled from static

characteristics of the tractor. These calculated values cannot compete with results of very expensive homologation tests, but it can be used in service applications, which demand lower accuracy.

The results in Tables 5, 6 and 7 and Fig. 7 show that the Zetor Forterra 8641 tractor won this comparison for the overall production of CO, CO<sub>2</sub> and NO<sub>x</sub> and also for fuel consumption. The tractor Case IH JX 90 dominates in the remaining two emission components (HC and PM). By contrast, the tractor Case IH JX 90 was better in terms of specific production of CO<sub>2</sub> (hence also fuel consumption) and PM. The tractor Fendt Farmer 412 Vario proved the lowest specific production of CO, HC and NO<sub>x</sub> production. Overall, the tractor Case IH JX 90 therefore seems to be the best from this point of view.

It should be taken into account that the presented comparison is only an example using the NRTC test modelling. The structures of the tractors are completely different because of their different age, and it is not possible to classify them into a single common power class. Also the numbers of hours worked are quite different for particular tractors and so the results can therefore be taken as an example of the use of modelling the NRTC test.

The knowledge of engines characteristics serves to describe the technical condition of the monitored machine. When engine characteristics are being used to keep the machine in good technical condition, it contributes to a better environment and, of course, financial savings due to fuel consumption reducing.

## Acknowledgements

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SMĚRNICE EVROPSKÉHO PARLAMENTU A RADY 97/68/ES ze dne 16. prosince 1997 o sblížení právních předpisů členských států týkajících se opatření proti emisím plyných znečišťujících látek a znečišťujících částic ze spalovacích motorů určených pro nesilniční pojízdné stroje.

SMĚRNICE EVROPSKÉHO PARLAMENTU A RADY 2000/25/ES ze dne 22. května 2000 o opatřeních proti emisím plyných znečišťujících látek a znečišťujících částic z motorů používaných k pohonu zemědělských a lesnických traktorů, kterou se mění směrnice Rady 74/150/EHS.

SMĚRNICE EVROPSKÉHO PARLAMENTU A RADY 2004/26/ES ze dne 21. dubna 2004, kterou se mění směrnice 97/68/ES o sblížení právních předpisů členských států týkajících se opatření proti emisím plyných znečišťujících látek a znečišťujících částic ze spalovacích motorů určených pro nesilniční pojízdné stroje.

SMĚRNICE KOMISE 2005/13/ES ze dne 21. února 2005, kterou se mění směrnice Evropského parlamentu a Rady 2000/25/ES týkající se emisí plyných znečišťujících látek a znečišťujících částic z motorů používaných k pohonu zemědělských a lesnických traktorů a kterou se mění příloha I směrnice Evropského parlamentu a Rady 2003/37/ES týkající se schvalování typu zemědělských a lesnických traktorů.