MODELING OF 8-MODE TEST PROCEDURE FOR ZETOR FORTERRA 8641 TRACTOR*

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The paper describes the modeling of 8-mode NRSC test procedure based on previously measured characteristics of carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), nitrogen oxides (NO_x) and particulates (PM). It makes possible to compare the current technical condition of an internal combustion engine of an agricultural tractor with the requirements of the certification test. Based on measured characteristics, it is also possible to model any other cycle without further measurements (NRTC test procedure, cycle for specific conditions – mountain tractor, etc.). Detection of the degradation of technical condition of the tractor and its early maintenance can help to improve the environment by reducing production of harmful substances emitted into the air and save money while reducing fuel consumption.

NRSC test procedure; fuel consumption; emission characteristics

INTRODUCTION

During operations of agricultural and forestry tractors, which are mainly driven by diesel engines, is releasing large quantities of gaseous emissions and particulate emissions from the exhaust pipe into the air. These are mainly carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), nitrogen oxides (NO_x) and particulates (PM). Due to the negative impact of these emissions on the environment, it has been proved necessary to limit legislatively the amount of pollutants produced by the engine (Brožová, 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 different character of the tractor engine work, the emission limits and methods of loading the engine during the certification measurements varies.

The 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 (Drabant et al., 2006). This test procedure is also often known as 8-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 change throughout the cycle. The waveform of this cycle was designed so that closely matches the real work of the engine during normal operation of the tractor.

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, NOx),
- NRTC test should be used for measurement of particulate emissions (PM) in stage IIIB and IV, it can also be used for issue approval in stage IIIA and measurement of gaseous pollutants (CO, HC, NOx) in stage IIIB and IV.

Emission approval guarantees that any new tractor put into operation does exceed emission limits. However, using a tractor as well as any other machinery is connected with wear of all its parts including the engine. This leads to the gradual increase in fuel consumption along with 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 production of solid particles because they measured

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Table 1. European emission limits for engines of agricultural and forestry tractors (g/kWh) (Bauer et al., 2006)

Net power (kW)	Emission component	Period of validity										
		2001	2002	2003	2006	2007	2010	2011	2012	2013	2014	20??
37–56	CO	6.5		5.0		5.0			**5.0**			
	HC	1.3		1.3		–			–			
	NO$_x$	9.2		7.0		–			–			
	NO$_x$ + HC	–		–		4.7			**4.7**			
	PM	0.85		0.4		0.4			**0.025**			
56–75	CO	6.5		5.0		5.0		**5.0**			**5.0**	
	HC	1.3		1.3		–		**0.19**			**0.19**	
	NO$_x$	9.2		7.0		–		**3.3**			**0.4**	
	NO$_x$ + HC	–		–		4.7		–			–	
	PM	0.85		0.4		0.4		**0.025**			**0.025**	
75–130	CO	5.0	5.0		5.0			**5.0**			**5.0**	
	HC	1.3	1.0		–			**0.19**			**0.19**	
	NO$_x$	9.2	6.0		–			**3.3**			**0.4**	
	NO$_x$ + HC	–	–		4			–			–	
	PM	0.7	0.3		0.3			**0.025**			**0.025**	
More than 130	CO	3.5		3.5			**3.5**			**3.5**		
	HC	1.0		–			**0.19**			**0.19**		
	NO$_x$	6.0		–			**2**			**0.4**		
	NO$_x$ + HC	–		4			–			–		
	PM	0.2		0.2			**0.025**			**0.025**		
stage I		stage II		stage IIIA			**stage IIIB**			**stage IV**		

only the smoke opacity of diesel engine using the free acceleration test procedure.

If, however, there are available current emission surfaces (dependence emissions from the 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 modeling of the homologation tests. Comparison of modelled test results (Hromádko et al., 2008; Kadleček et al., 2002) with the requirements of the Directives in order to establish the actual rate of degradation of emission characteristics of the engine in comparison to the legislative requirements for the new engine. Comparison of modelled test results (Hromádko et al., 2008; Kadleček et al., 2002) with the requirements of the Directives allows determination of the extent of degradation of emission characteristics of the engine in comparison to the legislative requirements for the new engine.

In this paper NRSC test procedure is modelled for Zetor Forterra 8641 tractor (Fig. 1) based on the measured emission characteristics (surfaces) and fuel consumption characteristic (Fig. 2).

MATERIAL AND METHOD

To the measured tractor Zetor Forterra 8641 there have been gradually attached the measuring apparatuses. The crucial part was weighting **hydraulic dynamometer** connected to tractor by rear power take-off with 540 revolutions/min (Fig. 3). The basic parameters of used dynamometer **AW NEB 400** are:

a. maximal torque of power take-off: 2850 Nm
b. maximal revolutions of power take-off: 3250 1/min
c. maximal braking power: 343 kW
d. error in measurement: 2%

Fig. 1. Zetor Forterra 8641 tractor

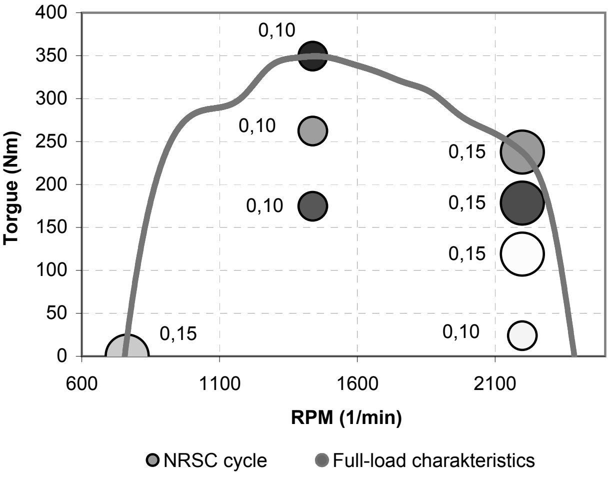

Fig. 2. NRSC test procedure – Zetor 8641

For the measurement of fuel consumption was used fuel box **(fuel consumption indicator)**, which consists of two flow indicators **Macnaught MSeries FlowMeter M2ASP-1R.** One fuel consumption indicator measures a quantity of fuel delivered to an engine and second one measures fuel quantity, which goes back to the tank (Fig. 4). The main parameters of flow indicator M2ASP-1R are:

e. maximal flow rate: 500 l/h
f. resolution: 400 pulses/l
g. error in measurement: 1%

Emissions were measured by combination of three apparatuses (Fig. 5), of which the most important one was analyzer **Atal AT 505** (CO, CO_2, HC, O_2, air temperature). Another apparatus was Atal AT 600, which measured smokiness and temperature of diesel. The last one was Asin FG34, which measured NO and as the control CO, CO_2, O_2.

Atal AT 505
– component – resolution – accuracy
h. CO – 0.01 % vol – 0.03 % vol or 5% read value
i. CO_2 – 0.1 % vol – 0.5% vol or 5% read value
j. HC – 1 ppm vol – 10 ppm vol or 5% read value
k. O_2 – 0.01% vol – 0,1% vol or 5% read value temperature – 1 °C – 2°C (read value)

Atal AT 600
– component – resolution – accuracy
l. opacity – 0.1% – 2%
m. temperature – 1 °C – 2 °C

Asin FG34
– component – resolution – range (overload)
n. NO – 1 ppm – 1000 ppm (4000 ppm)

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

NRSC test procedure consists of a series of eight modes of speed and torque, which characterizes the typical operation of the tractor engine. Individual modes and their weighting factors are shown in Table 2. The meaning of individual parameters of the test cycle is as follows:

- *rated speed* shall mean the maximum full load speed allowed by the governor as specified by the manufacturer,
- *intermediate speed* shall mean that engine speed which meets one of the following requirements:
    - for engines which are designed to operate over a speed range on a full load torque curve, the intermediate speed shall be the declared maximum torque speed if it occurs between 60% and 75% of rated speed,
    - if the declared maximum torque speed is less than 60% of rated speed, then the intermediate speed shall be 60% of the rated speed,

Table 2. NRSC test procedure – individual modes and their weighting factors

Mode No	Engine speed	Load (%)	Weighting factor
1	Rated	100	0.15
2	Rated	75	0.15
3	Rated	50	0.15
4	Rated	10	0.10
5	Intermediate	100	0.10
6	Intermediate	75	0.10
7	Intermediate	50	0.10
8	Idle	–	0.15

Fig. 3. Dynamometer AW NEB 400

Fig. 4. Fuel consumption indicator Macnaught MSeries FlowMeter M2ASP-1R

Fig. 5. Emission analyzer Atal AT 505

- ○ if the declared maximum torque speed is greater than 75% of the rated speed then the intermediate speed shall be 75% of rated speed,
- *load* shall mean the fraction of the maximum available torque at an engine speed,
- *weighting factor* shall mean the weight of the mode to calculate the resulting emissions.

The specific emission (g/kWh) shall be calculated for all individual components according to the formula (1):

$$MS = \frac{\sum_{i=1}^{8} (GH_i \cdot VF_i)}{\sum_{i=1}^{8} (P_i \cdot VF_i)} \tag{1}$$

where: MS – specific emissions of individual component (g/kWh)
GH_i – mass flow of individual component in mode i (g/h)
VF_i – weighting factor of mode i (–)
P_i – engine power in mode i (kW)

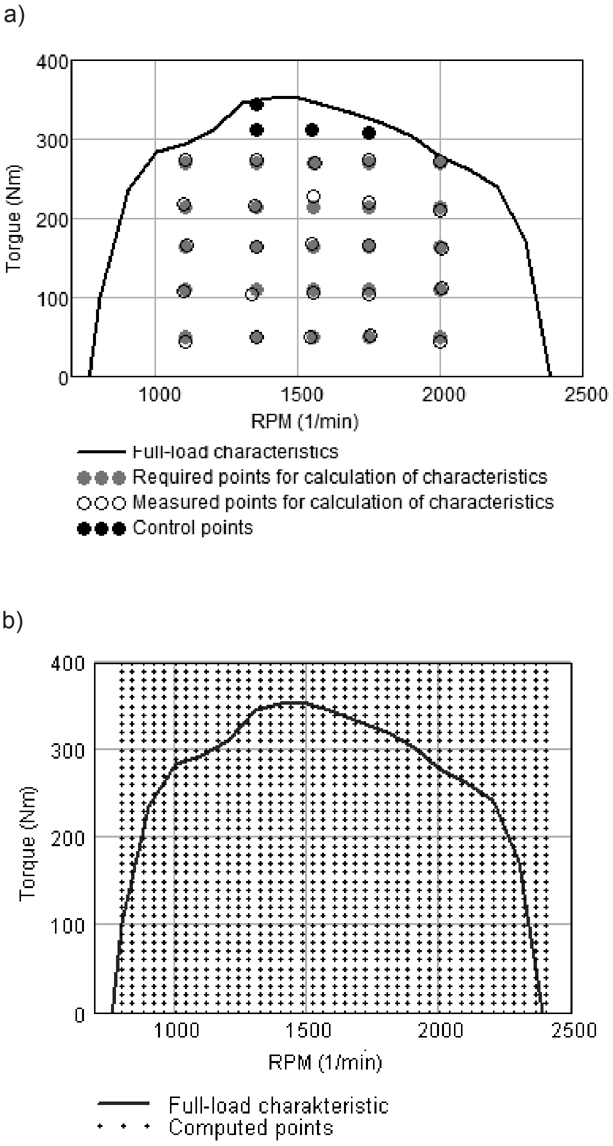

Fig. 6. Points for determining surfaces: a) measured, b) calculated

Twenty-five measuring points and four checkpoints were chosen to create consumption and emissions surfaces. The points that were selected for measurement according to tabulated engine data are depicted using grey color in Fig. 6a. The points in which fuel consumption and emissions were actually measured are depicted in white and then the surfaces were formed from these points. Measuring in black points served as the checkpoints in the area of maximal torque for mathematically created surfaces. All surfaces are limited by 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. 6b) from above surfaces. Examples of the resulting matrix are shown in a contour graph in Fig. 7.

RESULTS

As input data for calculation are required idle speed (765 1/min), rated speed (2200 1/min) and intermediate speed (1439 1/min). Other inputs for calculations are dependent of fuel consumption and emission production (g/h) on engine speed and torque (see above mentioned surfaces). The 8-point matrix ***e8*** for the calculation was prepared based on data of engine speed and torque according to Table 2 (Brožová, Růžička, 2009). The first column is the engine speed $(e8)_{i,0}$, in the second column there is the engine load $(e8)_{i,1}$ and in the third column is the weighting factor $(e8)_{i,2}$.

The matrix of 1681 points was interpolated using function (Draband et al., 2006) so that at any particular point was known processed quantity. ***Plocha*** is a matrix of 1681 points, ***PlochaXY*** indicates coordinates of engine speed ***om*** and torque ***TM***. Functions ***interp*** and ***cspline*** create together continuous surface ***Plocha(om, TM)***.

$$e8 := \begin{pmatrix} \text{"x(ot/min)"} & \text{"ye(Nm)."} & \text{"w"} \\ n_j & 1 \cdot M_j & 0.15 \\ n_j & 0.75 \cdot M_j & 0.15 \\ n_j & 0.5 \cdot M_j & 0.15 \\ n_j & 0.1 \cdot M_j & 0.10 \\ n_m & 1 \cdot Mm & 0.10 \\ n_m & 0.75 \cdot Mm & 0.10 \\ n_m & 0.5 \cdot Mm & 0.10 \\ n_v & 0.000001 & 0.15 \end{pmatrix}$$

$$e8 := \begin{pmatrix} \text{"x(ot/min)"} & \text{"ye(Nm)."} & \text{"w"} \\ 2200 & 240 & 0.15 \\ 2200 & 180 & 0.15 \\ 2200 & 120 & 0.15 \\ 2200 & 24 & 0.10 \\ 1439 & 353 & 0.10 \\ 1439 & 264.75 & 0.10 \\ 1439 & 176.5 & 0.10 \\ 765 & 0 & 0.15 \end{pmatrix} \tag{2}$$

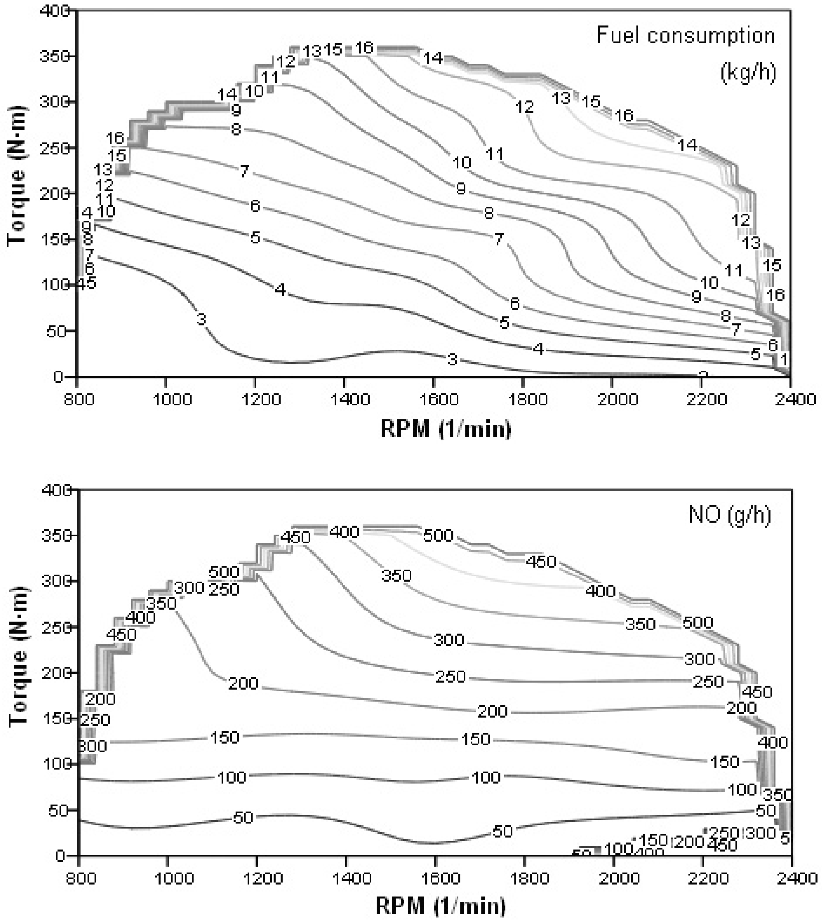

Fig. 7. The surfaces of hourly fuel consumption and hourly NO_x emission – Zetor Forterra 8641 tractor

$$\text{Plocha(om,TM)}:= \qquad (3)$$

$$=\text{interp}\left[\text{cspline(PlochaXY,Plocha),PlochaXY,Plocha,}\begin{pmatrix}\text{om}\\ \text{TM}\end{pmatrix}\right]$$

The calculation of specific emissions and fuel consumption will then take place in several steps:

1. Calculation (4) the weighted average of engine power ***P*** (kW)

$$P := \sum_{i=1}^{8} \frac{(e8)_{i,0} \cdot (e8)_{i,1}}{30000} \cdot (e8)_{i,2} \qquad (4)$$

2. Calculation (5) the weighted average of production quantity ***GH*** (g/h)

$$GH := \sum_{i=1}^{8} \text{Plocha}\left[(e8)_{i,0} \cdot (e8)_{i,1}\right] \cdot (e8)_{i,2} \qquad (5)$$

3. Calculation (6) specific production of the quantity ***MS*** (g/kWh)

$$MS := \frac{GH}{P} \qquad MS := \frac{\sum_{i=1}^{8} \text{Plocha}\left[(e8)_{i,0} \cdot (e8)_{i,1}\right] \cdot (e8)_{i,2}}{\sum_{i=1}^{8} \frac{(e8)_{i,0} \cdot (e8)_{i,1}}{30000} \cdot (e8)_{i,2}} \qquad (6)$$

By applying above relations (4–6) for each of quantity surfaces (CO, CO_2, NO_x, HC, PM and fuel consumption) are calculated the emissions of Zetor Forterra 8641 tractor on 8-point NRSC test procedure.

DISCUSSION AND CONCLUSION

The final Table 4 is formed by comparing modelled results in Table 3 with the European emission limits in Table 1 (Zetor Forterra 8641 tractor should meet limits in the stage II). From this, it is evident at first sight that the CO and HC the limit is met, while for NO_x and PM the limit is exceeded approximately 45–50%.

The increase above the legislative limits can be due to a number of causes, out of which most likely is a degradation of technical condition of the tractor.

The advantage of this method of modelling test cycles is that if there are available credible emission characteristics, any cycle can be modelled. This means that you can also model NRTC test procedure or any cycle designed for specific conditions (eg, tractor work in mountainous conditions, etc.) without any other additional measurements (Pexa, 2005).

The disadvantage of this method is acquiring of characteristics of the engine, which is more demanding because twenty-five points have to be measured (in this example). That is three times more points against the NRSC

Table 3. Resulting values for NRSC test procedure

Quantity	Weighted average of watched quantity (g/h)	Weighted average of engine power (kW)	Weighted average of watched quantity (g/kWh)
Fuel consumption	8 795	31.2	**282.1**
CO	66.11		**2.12**
CO_2	34 269		**1099**
NO_x	322.8		**10.35**
HC	1.77		**0.057**
PM	19.41		**0.62**

Table 4. Compared results of calculated values with European emissions regulations for Zetor Forterra 8641 tractor for NRSC test procedure

Quantity	Modeled value (g/kWh)	Emission limit value (g/kWh)	Result
CO	2.12	5.0	meets limit
HC	0.057	1.3	meets limit
NO_x	10.35	7.0	does not meet limit
PM	0.62	0.4	does not meet limit

test procedure. However, it can be assumed that the degradation of the technical conditions of tractor engine has an impact on changing of measured characteristics of the engine. This change can be noticed by measuring several significant points, and so the previously measured characteristics of the engine can be adjusted into a form that corresponds to the engine's new technical conditions.

Knowledge of engines characteristics serves to describe the technical state of the monitored machine. When engine characteristics are used to keep the machine in good technical conditions, it contributes to better environment and of course, financial savings, which will be caused due to reducing fuel consumption.

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Modelování 8-bodového cyklu – Zetor Forterra 8641.

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Příspěvek popisuje možnost modelování 8-bodového NRSC cyklu na základě měřených charakteristik oxidu uhelnatého (CO), oxidu uhličitého (CO_2), nespálených uhlovodíků (HC), oxidů dusíku (NO_x) a pevných částic (PM). Ve srovnání s homologačním testem nebo s předchozím vývojem lze tak stanovit technický stav spalovacích motorů zemědělských nebo lesnických traktorů. Současně však lze na základě měřených veličinových charakteristik modelovat libovolný jiný cyklus bez dalšího měření (NRTC cyklus, cyklus pro specifické podmínky – horský traktor apod.). Odhalením zhoršujícího technického stavu traktoru a jeho včasnou údržbou lze přispět ke zlepšení životního prostředí snížením produkce škodlivých látek vypouštěných do ovzduší a současně uspořit peníze sníženou spotřebou paliva.

NRSC cyklus; spotřeba paliva; emisní charakteristiky

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