Effect of rapeseed methyl ester on emission production

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Abstract

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This paper describes the effect of a mixture of rapeseed methyl ester and diesel oil on emission production of tractor engine. The hydraulic dynamometer was used to load the engine of Zetor Forterra 8641 tractor over rear power take-off. The measured tractor is almost new with less than 100 h worked. The measurements were realized for several ratios of diesel oil and rapeseed methyl ester (from pure diesel to pure rapeseed methyl ester). The engine was loaded by the dynamometer in several working points which were predefined by engine speed and its torque. The production of carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), nitrogen oxides (NO_x) and particulate matter (PM) were measured in each of these points. The comparison of different fuels was performed using the Non-Road Steady Cycle (NRSC) test procedure. Engine maps were also created for each emission component and for all of tested fuels.

Keywords: biofuel; ecology; NRSC; engine characteristic

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_2), hydrocarbons (HC), nitrogen oxides (NO_x) and particulates (PM). Due to the negative impact of these emissions on the environment, it proved necessary to impose legislative limits on 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 vary.

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 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 8-mode cycle, because it prescribes testing the engine in eight different modes. Newer Non-Road Transient Cycle (NRTC) test procedure 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 it closely matches the real work of the engine during normal operation of the tractor.

The total amount of hazardous exhaust emission components which are produced in agriculture is

Table 1. Selected technical requirements for diesel and rapeseed methyl ester (ČSN 65 6507 1994, ČSN EN 590 2010)

Requirements	Units	Diesel fuel	Rapeseed methyl ester
Density at 15°C	kg/m^3	820–860	870–890
Kinematic viscosity at 40°C	mm^2/s	2.0–4.5	3.5–5.0
Freezing point	°C	–4/–22	–8/–20
Flash point	°C	over 55	over 110

dependent on the total consumption of diesel fuel (Fig. 1), the number of tractors, their age and their technical condition. The statistics show that the total number of tractors is currently falling in the Czech Republic. The decrease is significant in the power category up to 60 kW. On the other side the number of tractors is growing in the category over 60 kW (Zelená zpráva 1999–2009). It is also significant that the tractor fleet is rejuvenated with new machines in the Czech Republic. New tractors use modern technologies like Common Rail fuel injection (such as New Holland, John Deere), injection of urea (AdBlue) into the exhaust system to reduce nitrogen oxides (e.g. New Holland, Case) and the use of fixed filters for reducing of particulates production from tractor engine (such as John Deere, Zetor).

Some types of biofuels may also contribute to reduce harmful emissions from internal combustion engines. Fatty acid methyl esters (FAME) and especially rapeseed methyl ester (RME) are the most widely used substitutes for diesel fuel. Although RME differs chemically from petroleum products, its density, viscosity, calorific value and process of combustion are very close to diesel fuel (Vančurová 2008). Table 1 lists the specific technical requirements for diesel oil and RME (ČSN 65 65071994; ČSN EN 590 2010).

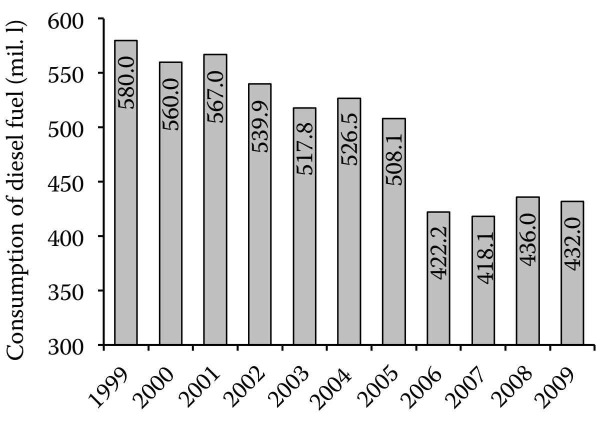

Fig. 1. Diesel fuel consumption in Czech agriculture (Zelená zpráva 1999–2009)

The literature says that in terms of power parameters the max. value will decrease by about 3–5% for the fuel with 31% content of RME. The fuel consumption will slightly increase by approximately 7% for this fuel. It is also necessary to take into account that RME evaporates worse than diesel and so it can enter the oil filling of the engine (Holas 1996).

Characteristics of internal combustion engines are used as proof of the properties of the engine (Bauer 2006). They are presented in graphic form and the measured values are often corrected to standard conditions according to applicable regulations or standards. The characteristic of the combustion engine means the relationship between the main engine operating parameters such as engine speed, torque (or mean effective pressure), power, specific fuel consumption, exhaust temperature, pressure of filling air etc. The basic characteristics are speed characteristic (RPM), load characteristic and engine map (total characteristic).

Any change in single characteristic indicates a change in engine settings or degradation of the technical condition of the engine which is affected by the operational wear (Müller et al. 2009). Emerging fault can be detected by checking these characteristics and so the maintenance or repair can be done timely. Engine characteristics can be measured on a roller dynamometer, on a dynamometer connected to rear power take-off or using dynamic measuring methods (Hromádko et al. 2007). Different driving cycles can be simulated based on mathematical modelling of these characteristics (Jílek et al. 2008; Brožová, Růžička 2009; Kubín, Pexa 2010; Pexa, Kubín 2010).

Tractor Zetor Forterra 8641 (Zetor Tractors, Brno, Czech Republic) which is located in the laboratories of the Department for Quality and Dependability of Machines, Faculty of Engineering, Czech University of Life Sciences in Prague was used to verify the effect of RME share in fuel on engine map of an internal combustion engine. Eight point NRSC test procedure was also realized for this tractor. The engine of the tractor had less than

Table 2. Basic technical parameters of the engine Zetor 1204 in Zetor Forterra 8641 tractor (manufacturer's data)

Parameter	Value
Rated power (kW)	60
Rated speed (min^{-1})	2,200
Max. torque (Nm)	351
Specific fuel consumption at rated power (g/kWh)	253

100 worked hours and laboratory measurements represent most of its previous work. Several ratios of diesel fuel and RME were selected as fuel. The ratios of diesel and RME are as follows:
– fuel No. 1 – 5.5% RME and 94.5% diesel fuel,
– fuel No. 2 – 19.7% RME and 80.3% diesel fuel,
– fuel No. 3 – 33.9% RME and 66.1% diesel fuel,
– fuel No. 4 – 48.0% RME and 52.0% diesel fuel,
– fuel No. 5 –100% RME.

MATERIAL AND METHODS

Measuring devices were gradually attached to the measured tractor Zetor Forterra 8641 (Table 2). Hydraulic dynamometer (Fig. 2) was connected to the rear power take-off of the tractor. Basic parameters of the dynamometer AW NEB 400 (AW Dynamometer, North Pontiac, USA) which was used are shown in Table 3. The fuel box which contains two flow meters Macnaught MSeries M2ASP-1R (Macnaught, Turrella, Australia) was used to measure fuel consumption of the engine. The first flow meter measures the amount of fuel supplied to the engine and the second flow meter measures the amount of fuel that returns to the tank. The main parameters of the flow meter M2ASP-1R are shown in Table 3. The individual emission components were measured using the BrainBee

Table 3. Basic technical parameters of the used measuring instruments

Parameter	Value
Dynamometer AW NEB 400	
Max. torque at power take-off (Nm)	2,850
Max. braking power at power take-off speed 540 min^{-1} (kW)	149
Error in measurement (%)	2
Flow meter M2ASP-1R	
Max. flow rate (l/h)	500
Resolution (pulses/l)	400
Error in measurement (%)	1

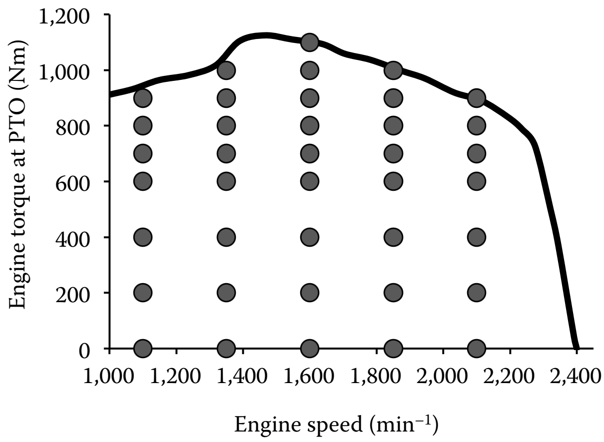

Fig. 2. An example of defined measurement points – 19.7% of RME

analyzers OPA 100 and AGS 200 (Brain Bee, Parma, Italy) (CO, CO_2, HC, NO, O_2, smoke and fuel temperature). The main parameters of the analyser are shown in Table 4. The amount of intake air was measured using lossless nozzle. Information about the amount of intake air was used to recalculate the values measured in percentages by analysers to weight units. The fuel tank of the tractor was completely disconnected during the measurement and an auxiliary tank for currently tested fuel which has 30 l capacity was used instead of it. No other modification of the tractor fuel system was performed. The following sensors were also connected: air temperature and pressure sensor, engine oil temperature sensor and fuel temperature sensor.

The tractor engine was warmed up after filling the tank with selected fuel to reach its operating temperature. The rated speed characteristic of the engine was measured after heating the engine (Fig. 2). This characteristic was used to determine

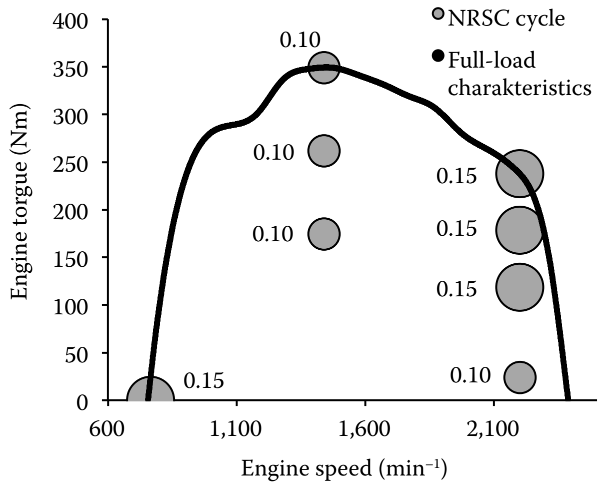

Fig. 3. NRSC test procedure – Zetor Forterra 8641

Table 4. Basic technical parameters of the BrainBee analyser

Component	Resolution	Accuracy
CO	0.01% vol	0.03% vol or 5% RV
CO_2	0.1% vol	0.5% vol or 5% RV
HC	1 ppm vol	10 ppm vol or 5% RV
O_2	0.01% vol	0.1% vol or 5% RV
NO	1 ppm	
opacity	0.1%	
temperature	1°C	2.5°C

RV – readed value

the appropriate measuring point for creating of the engine map (Fig. 4). The measurement points (about 35) are defined so that most of them are in the working area of the engine. Defining of these points was followed by their measurement. After turning the power take-off on the dynamometer and the governor of engine speed were set so that the engine has stabilized in the desired measuring point. Engine speed, torque, fuel consumption, emission production and other monitored quantities were registered after stabilization of the engine. Engine power was then calculated from engine speed and its torque.

Values of torque and shaft speed which were measured on power take-off were converted to engine values using the appropriate gear ratio (3.543). The power losses in transmission between the engine and power take-off which can be regarded as constant are not significant for comparison of the effect of fuel type on engine map. Therefore these losses are not considered in the evaluation of measurement. So the calculated values of specific emission production correspond to engine power on the power take-off.

Measured values were then processed using functions of the MathCAD software into continuous surfaces. Regress and Interp functions were used to create continuous surfaces. Surfaces thus created are stored in a file in a text format, where a matrix of 41 × 41 points is created (1681 points). Spline function is used in further work with this matrix. This function which uses interpolation from points of the matrix allows determining the value of a monitored variable at any engine operating point.

The points for the NRSC homologation cycle were measured simultaneously with the measurement points for the engine map (Fig. 3). NRSC test procedure consists of a series of eight modes of speed and torque, which characterize the typical operation of the tractor engine. Individual modes and their weighting factors are shown in Table 5. The meaning of individual parameters of the test cycle is as follows:

- *rated speed* shall mean the max. 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 max. torque speed is less than 60% of rated speed, then the intermediate speed shall be 60% of the rated speed,
  - if the declared max. 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 max. available torque at the 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 Eq. (1):

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

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)

Table 5. 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

Table 6. Measured points and measured and calculated value of emission components for fuel containing 48% RME

Point No.	Engine speed (min^{-1})	Dynamometer torque at PTO (N.m)	Production of emission components (g/h)					Fuel consumption (kg/h)	
			CO	CO_2	HC	NO	PM	emission	flow meter
0	726	0	24.7	5,233	0.29	91	0.23	1.7	1.2
1	1,644	22	49.3	14,317	1.04	78	0.99	4.5	3.5
2	1,649	191	51.4	19,804	0.64	140	1.85	6.3	4.7
3	1,649	413	27.0	27,172	0.74	299	1.76	8.6	7.0
4	1,649	600	29.2	34,888	0.35	483	2.03	11.0	8.8
5	1,649	699	30.4	39,604	1.13	553	3.63	12.5	9.6
6	1,650	811	31.9	44,119	0.79	616	5.46	13.9	10.9
7	1,649	897	66.7	47,717	0.99	676	6.96	15.0	12.0
8	1,649	1,013	106.7	54,742	1.73	735	15.45	17.3	13.6
9	1,107	12	46.0	7,233	0.53	60	0.31	2.3	1.8
10	1,102	198	31.6	11,907	0.52	119	0.44	3.8	3.0
11	1,100	409	16.2	17,841	0.55	303	0.48	5.6	4.3
12	1,100	609	83.2	24,344	0.31	376	1.12	7.7	5.7
13	1,097	764	409.8	29,818	0.58	388	5.75	9.6	7.6
14	1,100	888	1,156.7	34,570	0.74	365	22.49	11.4	8.3
15	2,103	29	70.7	21,675	0.56	84	3.13	6.9	5.4
16	2,105	219	77.7	29,307	0.99	167	3.25	9.3	7.4
17	2,099	390	42.5	37,425	0.76	276	3.35	11.8	9.3
18	2,099	607	47.1	48,057	0.70	511	3.06	15.1	12.3
19	2099	701	49.4	52,807	1.86	599	4.01	16.6	13.6
20	2,103	833	109.1	62,572	1.62	720	10.51	19.7	15.8
21	1,405	18	40.1	9,769	0.79	60	0.77	3.1	2.4
22	1,396	208	40.8	15,708	0.64	125	1.19	5.0	3.8
23	1,402	395	21.4	21,854	0.39	263	1.34	6.9	5.4
24	1,402	608	45.0	29,696	0.43	452	2.69	9.4	7.3
25	1,396	708	70.2	33,864	1.03	501	4.80	10.7	8.3
26	1,398	806	122.1	38,355	0.91	540	9.36	12.1	9.5
27	1,400	909	195.2	42,624	0.84	571	12.52	13.5	10.3
28	1,400	947	259.8	44,627	0.92	574	16.68	14.2	11.0
29	1,853	27	86.5	16,303	1.17	69	1.81	5.2	4.0
30	1,845	205	61.1	23,538	0.93	139	2.48	7.4	6.0
31	1,846	403	32.8	30,967	1.34	274	3.32	9.8	8.0
32	1,847	617	36.2	40,983	1.61	485	3.38	12.9	10.2
33	1,849	701	37.7	44,432	1.53	565	4.00	14.0	11.3
34	1,849	820	40.5	50,906	1.79	665	5.40	16.0	13.0
35	1,849	939	87.1	57,504	2.06	737	12.55	18.1	14.4
NRSC									
0	726	0	24.7	5,233	0.29	91	0.23	1.7	1.2
36	1,548	519	25.3	29,400	0.76	374	2.42	9.3	7.4
37	1,552	777	56.3	40,229	0.83	561	5.16	12.7	9.8
38	1,548	1025	137.1	51,135	1.40	685	17.54	16.1	12.7
39	2,194	71	79.4	24,314	1.16	101	4.01	7.7	6.2
40	2,197	371	46.3	39,308	1.47	263	4.33	12.4	10.0
41	2,200	568	51.0	48,923	1.90	461	3.20	15.4	12.5
42	2,200	745	57.5	61,390	1.46	589	9.84	19.3	14.9

NRSC – Non-Road Steady Cycle; RME – rapeseed methyl esters; PM – particulate matter

Table 7. Results of NRSC test procedure of tractor Zetor Forterra 8641 with different proportions of RME in diesel fuel (g/kWh)

Proportion of RME (%)	CO (g/kWh)	HC (g/kWh)	NO (g/kWh)	PM (g/kWh)	CO_2 (g/kWh)	Flow meter (g/kWh)
5.5	3.10	0.040	12.00	0.32	1,196	289
19.7	2.56	0.034	12.84	0.12	1,165	278
33.9	3.00	0.050	11.87	0.08	1,185	298
48.0	1.83	0.038	12.36	0.18	1,219	304
100	1.68	0.032	13.86	0.04	1,162	326

for abbreviations see Table 6

RESULTS

Table 6 shows an example of the measured values of emission components for the blended fuel which contains 48% RME. Similar results were achieved for other ratios of diesel fuel and RME.

The performed measurements confirmed that an increasing proportion of RME in the fuel decreases the max. power and torque of the engine (Figs 4 and 5). However, the decrease does not exceed 10% of the max. value of the engine operating on pure diesel. The max. power and torque of the engine are moved towards to higher engine speed when using fuel with RME.

NRSC test is evaluated using formula Eq. (1) from the eight measured points that are listed at the bottom of the Table 6. The resulting values for all ratios of RME and diesel are given in Table 7. It is obvious from Table 7 that an increasing proportion of RME is reflected by reducing emissions of carbon monoxide (CO), hydrocarbons (HC), particulates (PM) and carbon dioxide (CO_2). On the other hand, a higher proportion of RME in fuel brought increased emissions of nitrogen oxides (NO) and increased fuel consumption (flow meter) as it was measured during the NRSC test procedure of tractor Zetor Forterra 8641.

NRSC cycle includes only a few important points at the rated engine speed and at the engine speed where the engine reaches its max. torque. Other operating areas of the engine (e.g. the area of max. power) are not described. NRTC test procedure reflects the behaviour of the engine better but it is much more demanding to measuring devices. Engine maps can be created for individual emission component or fuel consumption. These maps allow graphical assessment of the impact of RME share in diesel fuel on emission or fuel consumption.

The function Regress together with the functions Interp (2) interleave the measured points in fuel consumption *PlochaZ* with preset cubic polynomial. *PlochaZ* is in coordinates *PlochaXY* (*om* and *TM* are coordinates of engine speed and torque). The result is a continuous surface *Plocha*(*om*, *TM*). A square matrix of 41 × 41 (1681 points) is created from this surface for further processing (Pexa, Kubín 2012).

The matrix of 1681 points is interleaved using the Spline function (3) in the further processing. The Spline function interleaves the surface exactly in the points which are defined in 41 × 41 matrix.

$$Plocha(om, TM) := \text{interp}\left[cspline(PlochaXY, Plocha), PlochaXY, Plocha, \left(\frac{om}{TM}\right)\right] \quad (3)$$

where:

Plocha – matrix of measured quantity in 1681 points (g/h)

cspline – the resultant spline curve is either cubic

The procedure of making surfaces Eqs (2) and (3) is applied to all of test fuels. Examples of the results are shown in form of engine maps in Figs 4 and 5 for NO, PM and CO_2.

Information about each mode of tractor engine can be found in these engine maps. The most economical or the most ecological operation mode of the engine can be found using created engine maps. It is also possible to watch important operating modes of the engine so the maintenance can be performed to restore the original parameters if it is needed. In addition, engine maps can be used for simulating any driving cycle of the tractor including cycles which model real field working operation. Specially designed driving cycles can be adjusted individually according to customer requirements so that they correspond to usual tractor operating mode and thus they describe changes in technical condition as accurately as possible.

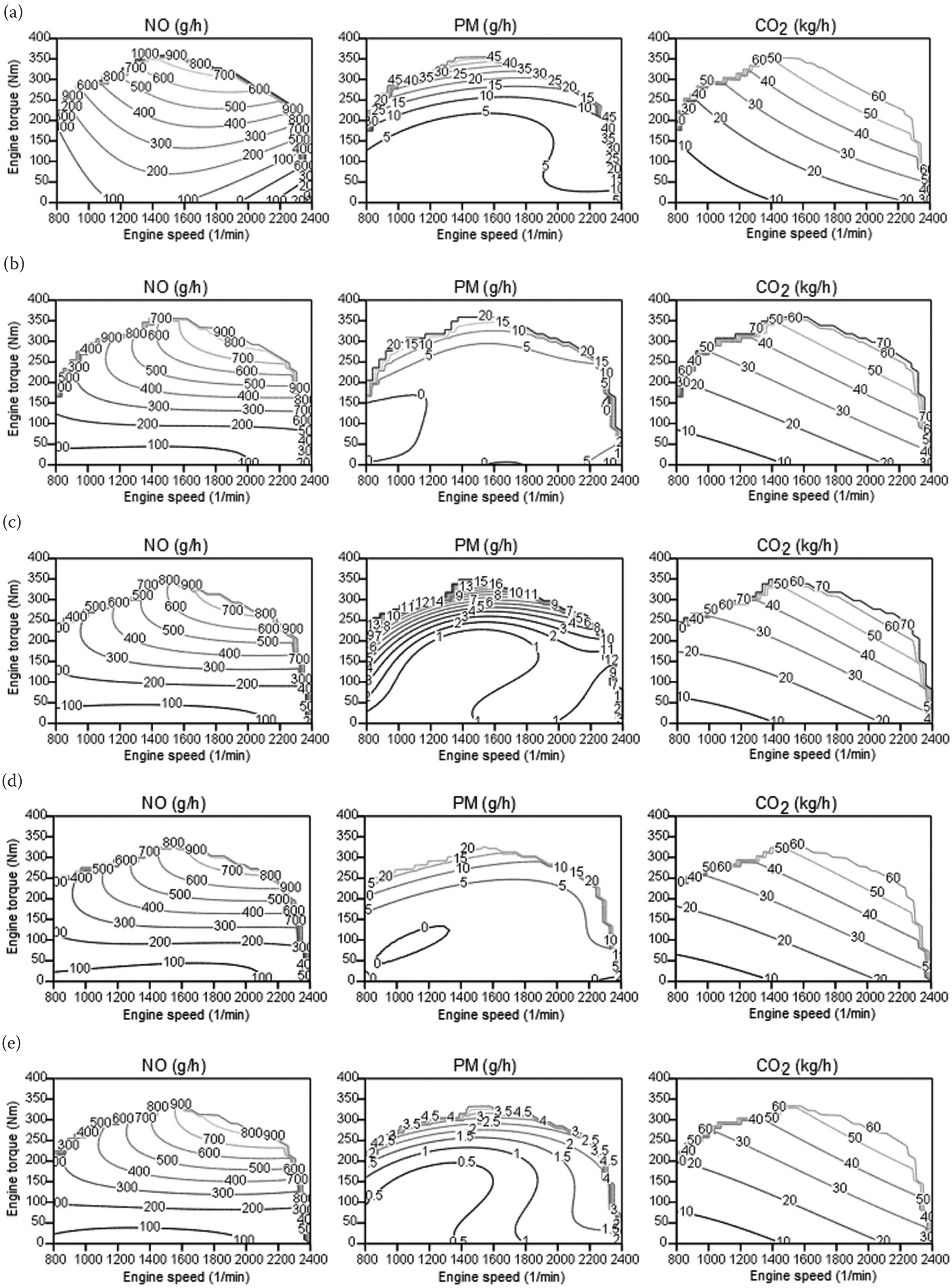

Fig. 4. Engine maps for fuel (a) No. 1 – 5.5% RME, (b) No. 2 – 19.7% RME, (c) No. 3 – 33.9% RME, (d) No. 4 – 48.0% RME, and (e) No. 5 – 100.0% RME

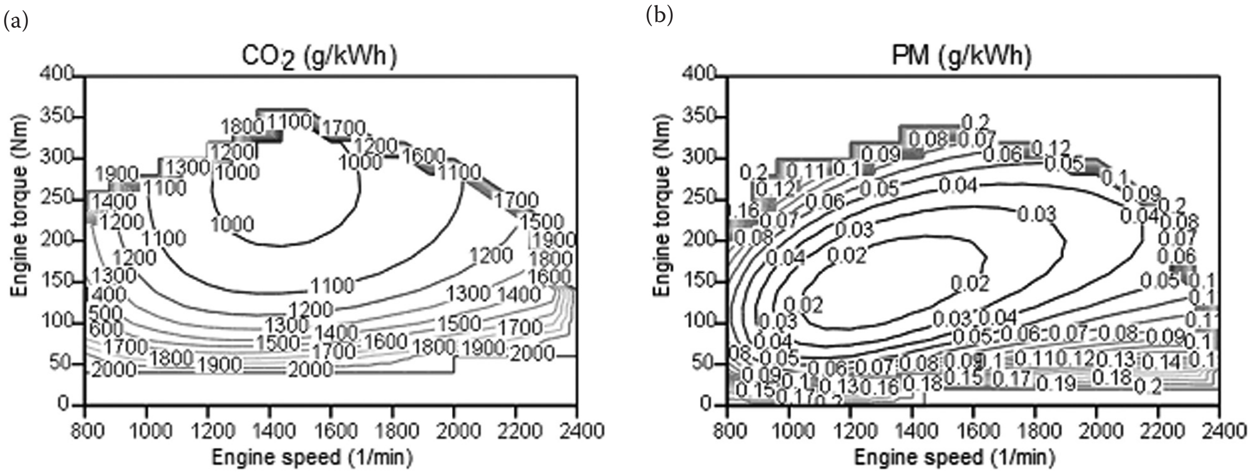

Fig. 5. Engine map for fuel (a) No. 3 – 33.9 % RME and (b) No. 5 – 100.0% RME

CONCLUSIONS

The increasing proportion of RME in diesel is in terms of engine performance parameters of tractor Zetor Forterra 8641 reflected in the decreasing value of the max. torque and power of the engine. This decrease in performance parameters did not exceed 10% of the max. value against the engine operating on pure diesel.

The measurement shows that an increasing proportion of RME in fuel is reflected by reducing emissions of carbon monoxide, hydrocarbons, particulates and carbon dioxide. On the other hand, a higher proportion of RME in fuel brought increased emissions of nitrogen oxides and increased fuel consumption (flow meter) for tractor Zetor Forterra 8641. Operating modes of the engine where it achieved min. specific fuel consumption and low specific emissions production remain essentially unchanged and the tractor can be operated in the same way in any proportion of diesel fuel and RME.

The choice of operating modes of the engine remains unchanged and so it is possible to operate the tractor in the same way. The advantage of using RME is also the ability to use it without any technical modification of the engine (most of the new engines is ready for using RME). However, it is necessary to take into account the properties of RME and it is also important to take care of fuel system, particularly with regard to the removal of water and the other sediments.

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