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Comparison of mechanical and electric drive of mulcher

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Abstract. The contribution is focused on comparison of mechanical and electric drive of mulcher with vertical axis of rotation by means of mathematical model. The mulcher has working width of 6 m and it is usually aggregated with tractor of minimal power of 150 kW. On the test plot the torque and power transferred trough the tractor PTO, fuel consumption and the production of gaseous emissions components were monitored. This field measurement served as a basis for modelling as well as measured complete characteristics of the combustion engine of the tractor John Deere 7930. As a main base for the modelling the record of real operation of the tractor with mulcher was used. Then, in the software product MathCad the operation of the tractor with mechanical and electrical drive of the mulcher was modelled. In the case of the electrical drive of the mulcher the tractor with internal combustion engine, connected to generator was taken into consideration. Due to overall lower efficiency of the electrical drive with generator, worse values of the fuel consumption and emissions production in comparison with mechanical drive were reached in case of electric drive. At hypothetical use of batteries (100% electro-powered tractor) and when the energy mix at Czech Republic is taken into consideration, it is possible to reach the quarter values of emissions production in comparison with combustion engine.

Key words: Electric drive, emissions, fuel consumption, mulcher.

INTRODUCTION

Globally it is put the pressure on manufacturers and also operators of machinery equipped by internal combustion engines in order to achieve the lowest fuel consumption and thus as low as possible production of harmful emissions. At the same time there are discussions between producers of engines and physicians related to the harmfulness of individual components of emissions. (Hirvonen et al., 2005; Xu & Jiang, 2010; Kvist et al., 2011; Jalava et al., 2012). Harmfulness of these individual components is generally well known, but the problem is to express it financially.

Legislative regulations are forcing the manufacturers to produce ever more sophisticated machines producing minimum quantity of harmful emissions (Ryu et al., 2014). Unfortunately, the testing of these machines is usually done only during the homologation measurements (Maass et al., 2009; Lijewski et al., 2013; Cordiner et al., 2014; Liu et al., 2015). Actual measurements in operational conditions have then only informative value and do not achieve sufficient accuracy in order to be able to prove, that the internal combustion engine of an used machine remains in compliance with homologation regulations.

Widely discussed issue relates to the evaluation of emissions in operational conditions, which is not easy (Dace & Muizniece, 2015). Measurement of emissions in operational conditions brings many pitfalls, such as precision of analyzers and speed of response to the rapid change of measured variables (Pexa et al., 2016). For the practice it would be much easier to monitor the regime of machine operation and then, on the basis of overall characteristics of engine, to quantify actually produced emissions.

Within the regular operational tests it would be then specified actual overall characteristics of engine. The operators of vehicles would be then taxed not only according to what machine they bought, but also how well they care of a given machine. Which means whether the characteristics are still close to the characteristics given by manufacturer, or whether the technical state of machine has changed so much, that these characteristics differ significantly from those, which were specified by manufacturer. It is also possible to include into assessment the kind of used fuel or biofuel, which has a significant effect on emissions (Sada et al., 2012; Repele et al., 2013; Hönig et al., 2014; Čedík et al., 2015a; Pexa et al., 2015).

At the present time there is solved, in addition to the issue of biofuels, the question of electric drive of vehicles, tractors, trucks and also agricultural machinery (Usinin et al., 2013; Raikwar et al., 2015; Moreda et al., 2016). This area of research is still at the beginning, but already now it is possible to predict, how it will be with relation of these machines to the environment. Hypothetically it can be assumed, that electric drive of agricultural machinery will have worse efficiency than in case of mechanical operation (depending on a condition of generator and a combustion engine of tractor). An electric drive of tractor solved by means of batteries, when electricity is produced in a power station, seems to be very interesting alternative (hypothetically the operation of tractors can be without emissions at use of solar energy, if the disposal of the batteries, panels etc. won't be included).

The aim of this contribution is to compare the mechanical and electric drive of a mulcher with vertical axis of rotation. For comparison there is used real run of the mulcher with the tractor and for analysis of fuel consumption and emissions production there are used a model and overall characteristics of the engine.

MATERIALS AND METHODS

In order to make a comparison of mechanical and electric drive of the mulcher, it was necessary to obtain at first the **overall characteristics of combustion engine of tractor**, which was John Deere 7930 tractor with nominal output of 150 kW on the PTO, which represents a requirement for Mulcher MZ 6000 (three rotors, working width of 6 m). This measurement was carried out in laboratory with use of dynamometer

(AW NEB 400 – accuracy 2%). At first there was measured external rotation speed characteristics and on the basis of it there were determined measurement points so, that as many as possible these points cover the working range of the engine. During the measurement there were determined the fuel consumption and emission parameters. With the use of functions in MathCad programme (especially interp and spline) there were worked out continuous surfaces in coordinates of engine speed and torque. An example of continuous surfaces for carbon dioxide and hydrocarbons is shown in Fig. 1.

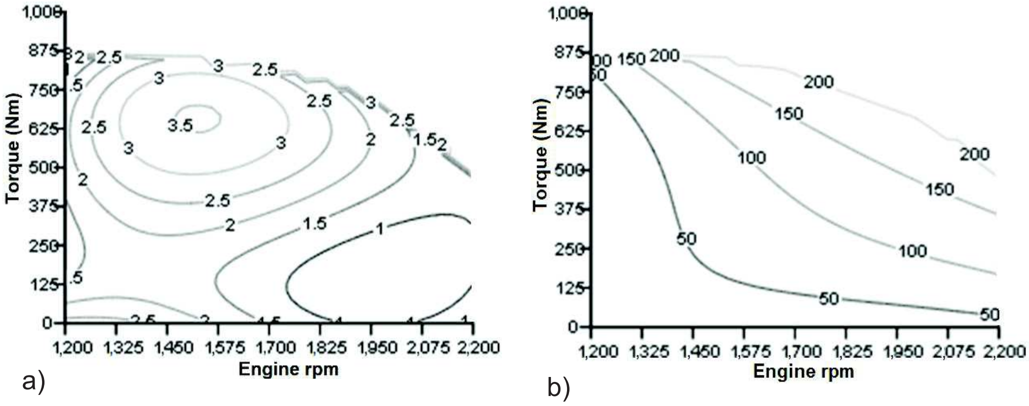


Figure 1. Continuous variable surfaces: a) hydrocarbons (g h^{-1}); b) carbon dioxide (kg h^{-1}).

Measurements in field conditions were carried out on a grassy plot. During the driving of a tractor set with mulcher there was measured the amount of consumed fuel by means of flow meter (AIC VERITAS 4004 – measurement error 1%). The amount of intake air, engine load, engine speed and tractor speed were measured by means of on-board diagnostics (on-board diagnostics system monitored by means of the device Texa Navigator TXTs – frequency 4 Hz). Performance required to drive of mulcher was measured by means of dynamometer (MANNER Mfi 2500Nm_2000U/min – accuracy 0.25%) and quantity of produced harmful emissions of carbon dioxide, carbon monoxide, hydrocarbons and nitrogen oxides by emission analyser VMK (Table 1). The movement of working set was monitored via GPS receiver (Qstarz BT-Q1000X – frequency 5 Hz) and by a drone. Recorded points are shown in external rotation speed characteristics of the tractor engine in Fig. 2. The trace of the real ride and engine parameters during this ride are shown in Fig. 3.

Table 1. Technical parameters of analyzer VMK (Kotek et al., 2016)

Measured component	Range	Resolution	Uncertainty of measurement
CO	0–10% vol	0.001% vol	0–0.67%: 0.02% absolutely, 0.67% – 10%: 3% from measured value
CO_2	0–16% vol	0.1% vol	0–10%: 0.3% absolutely, 10–16%: 3% f. m. v.
HC	0–20,000 ppm	1 ppm	10 ppm or 5% f. m. v.
NO_X	0–5,000 ppm	1 ppm	0–1,000 ppm: 25 ppm, 1,000–4,000 ppm: 4% f. m. v.

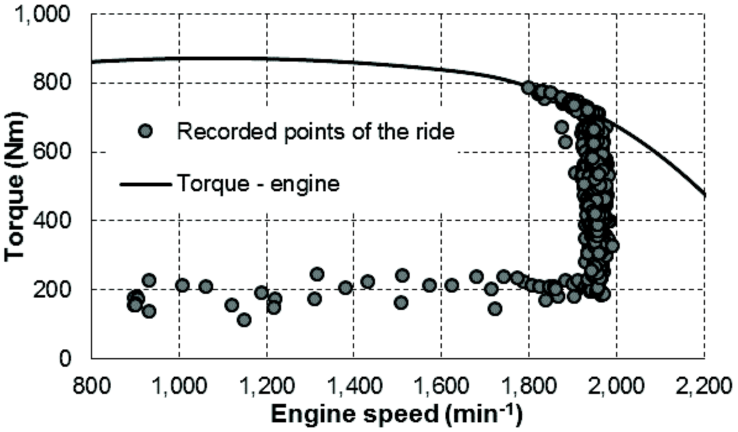
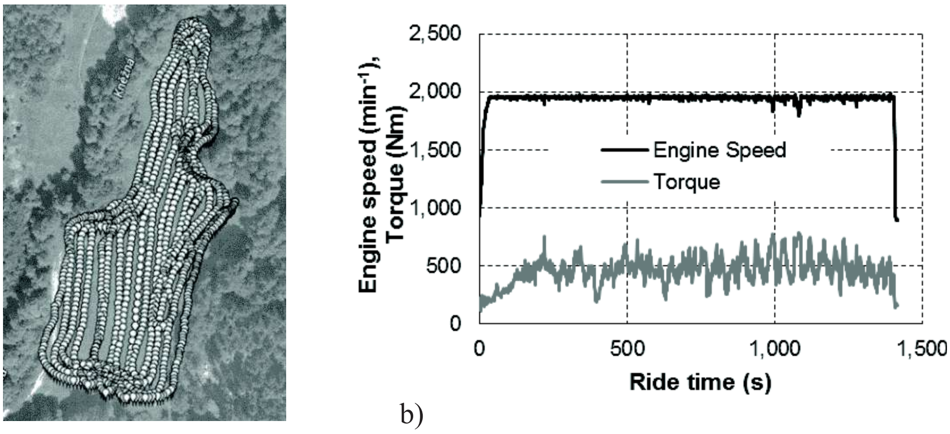


Figure 2. Recorded points of the real ride of the mulcher in external speed characteristics of the tractor engine.



a) b)

Figure 3. Field measurement: a) measured points, b) parameters of run.

The model include also **losses of mechanical drive of mulcher depending on engine speed**, which was measured over a flat surface in working height of 5 cm. For the measurement the dynamometer (MANNER Mfi 2500Nm_2000U/min – accuracy 0.25%) was used. Resulting values are described in Čedík et al. (2016) and Čedík et al. (2015b; 2015c).

In terms of electric drive of mulcher it is necessary to create dependency of efficiency of electric energy transmission from the engine to the shaft of mulcher. The transmission of electric energy takes place in the following way: At the start there is an internal combustion engine, which drives AC generator. It follows the rectification of electric energy and its transfer to mulcher. In mulcher there is a change from DC energy to AC energy. All these changes, transmission and proper electric engine are working with a certain efficiency. The overall efficiency of electric energy transmission is show in Fig. 4. Due to the parameters of electric engine (Table 2) there is used a gearbox, which reduces electric engine speed to 1,000 rpm of the PTO shaft, while the electric engine operates at 3,000 rpm, when achieves maximum torque (450 Nm) and power output (140 kW).

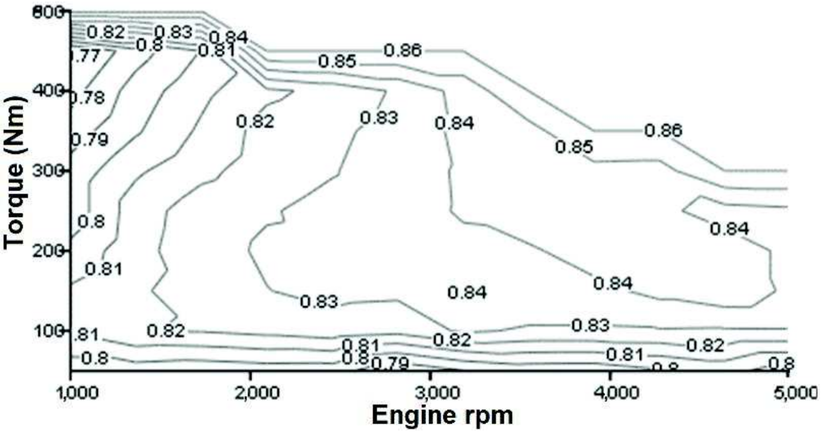


Figure 4. Overall efficiency of electric energy transmission.

Due to the substantial reduction of overall efficiency of electric energy transmission in comparison with mechanical energy transmission it was necessary to modify the parameters of really recorded run. Parameters of run were modified so, that the load of mulcher has been reduced to 70%. It could be applied, when a mulching was carried out on a plot with lower yield, however it is typical for the work of mulcher, for example in case of the ungrazed patches. If this situation didn´t occur, the engine load would be on external characteristics and consequently there would occur a considerable reduction in engine speed. The proper model comparison of mechanical and electric drive of mulcher would be by this change considerably affected.

Table 2. Basic parameters of the electric motor (STV Technic, 2017)

powerMELA®-C 140kW		
Nominal power	140	kW
Traction net voltage	650	V_{dc}
Traction net current	229	A_{dc}
Phases	2 x 3	-
Nominal torque	450	Nm
Nominal speed	3,000	min^{-1}
Maximum speed	6,000	min^{-1}
Maximum torque	608	Nm
Maximum power	154	kW
Efficiency	95.4	%
Weight	147	kg

As a second variant it is possible to utilize the easily controlled speed of the electric drive and to reduce the cutting speed of the mulcher's rotors from 105 m s^{-1} (1,000 rpm) to 84 m s^{-1} 800 rpm in order to reduce aerodynamic losses.

As another variant it could be possible to run the combustion engine of the tractor in lower rotation speed in order to increase the engine efficiency. Also, the combination of the reduction of combustion engine speed and electric engine speed was taken into consideration.In order to complete the model of electrical drive, it was removed from the run with mechanical mulcher the requirement for drive of the tractor itself. The required torque for tractor run without attached mulcher is shown in Fig. 5.

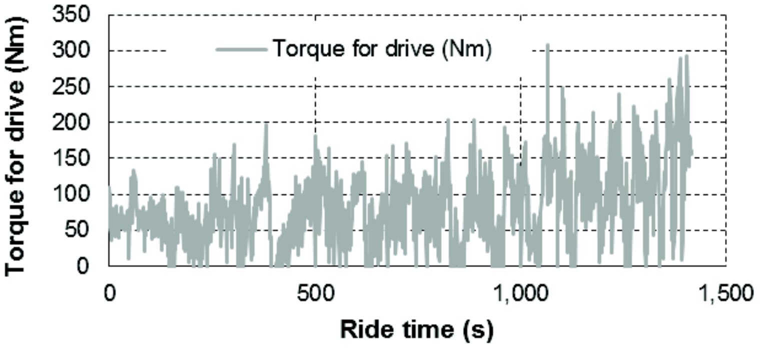


Figure 5. Requirement of engine torque for tractor run.

RESULTS AND DISCUSSION

In Fig. 6 there is shown the course of necessary engine torque in case of attached mechanical and electrical drive of mulcher. From this figure it is obvious, that for electrical drive it is necessary to have higher torque, than in case of mechanical drive.

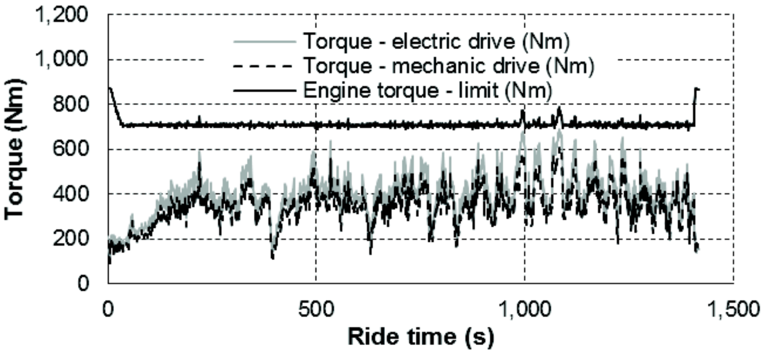


Figure 6. Course of load of the tractor engine (drive of the tractor with connected mulcher + drive of mechanism of the mulcher) in case of mechanical and electric drive of mulcher.

Owing to the need of higher torque for electric drive of mulcher, it can be expected, that the fuel consumption and emissions production of combustion engine will be also higher. In order to achieve a reduction of fuel consumption and emissions, it is possible to utilize the ability to easily regulate electric drive of mulcher and to reduce its working speed. After reduction of mulcher rotors speed from normal operating 1,000 rpm (cutting speed 105 m s^{-1}) to 800 rpm (cutting speed 89 m s^{-1}), it can be achieved the reduction of mulcher aerodynamic losses by almost 1/2 and thus also a reduction of fuel consumption and emissions production, as was already published by Čedík et al. (2016). It is also possible to reduce, as another variant, the engine speed for drive of generator (reduced by 280 rpm) so that the engine will be running with better efficiency. In this case the course of load is shown in Fig. 7.

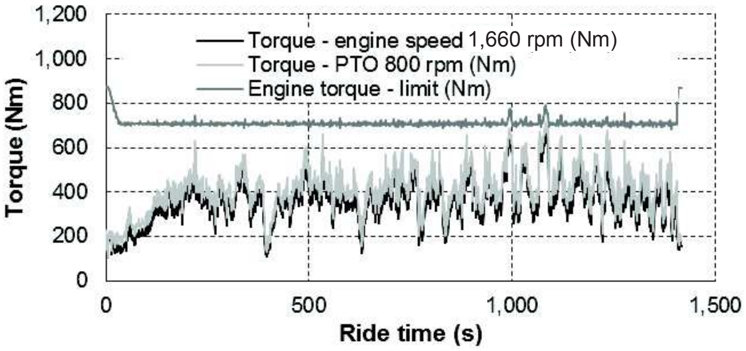


Figure 7. Course of load of the tractor engine (drive of the tractor with connected mulcher + drive of mechanism of the mulcher) in case of reduced speed of the mulcher and combustion engine.

In Fig. 8 there is shown the course of fuel consumption, NO_X production and smoke emissions from combustion engine during the run cycle, when a) represent standard mechanical drive and b) standard electric drive.

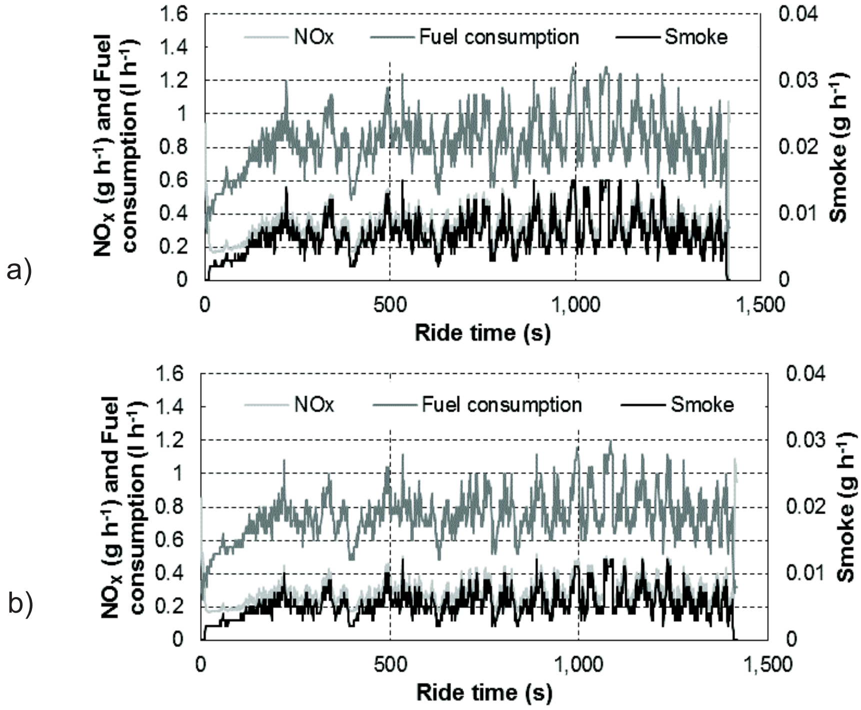


Figure 8. Course of fuel consumption, NO_X production and smoke emissions from combustion engine during the run cycle, when a) represent standard mechanical drive, b) standard electric drive.

Values for the entire run cycle are shown in the Table 3, where they are converted to one hour of tractor operation. For each of variant there are calculated two values of fuel consumption and amount of emissions. The first value is based on the sum of fuel consumption and emissions production that was calculated for each recorded point of run. The second value is based on average engine speed and average load and it is single value deducted from the overall characteristics of engine.

Table 3. Fuel consumption and production of emissions converted to one hour of operation

	Fuel consumption $l\ h^{-1}$	CO_2 $kg\ h^{-1}$	CO $g\ h^{-1}$	NO $g\ h^{-1}$	HC $g\ h^{-1}$	PM $g\ h^{-1}$
Electric drive	29.32	128.93	275.65	482.20	1.44	9.61
Electric drive - average	29.01	128.48	276.41	448.67	1.49	8.96
Mechanical drive	26.32	118.31	245.88	410.30	1.25	7.61
Mechanical drive - average	25.86	118.54	244.23	378.04	1.26	7.14
Electric drive	27.24	121.29	254.82	433.17	1.30	8.24
Electric drive - average	26.75	121.44	253.32	397.35	1.33	7.63
Mechanical drive	24.67	111.86	228.98	374.99	1.13	6.64
Mechanical drive - average	24.08	112.42	225.91	340.95	1.12	6.20
Electric drive	32.72	103.35	289.88	611.01	2.64	6.84
Electric drive - average	33.33	100.45	290.90	612.03	2.77	5.84
Mechanical drive	28.89	93.54	246.51	545.21	2.37	5.08
Mechanical drive - average	29.04	92.22	242.88	535.81	2.43	4.32
Electric drive	29.95	96.49	259.14	564.26	2.44	5.67
Electric drive - average	30.28	94.48	256.60	557.91	2.53	4.71
Mechanical drive	26.42	88.36	221.03	504.05	2.19	4.33
Mechanical drive - average	26.42	87.65	215.06	489.82	2.22	3.61

Great potential can be seen in purely electric drive of tractor. If there would be available a sufficient electric energy accumulator, into which this energy would be filled from the energy mix of the Czech Republic, in that case the produced emissions will be by 1/3 lower at least, than emissions from combustion engine. In case of the use of electric energy purely produced by coal-fired power station, the produced emissions will be comparable to the emissions produced by combustion engine.

CONCLUSIONS

This contribution is aimed at comparison of mechanical and electric drive of mulcher. Comparison is carried out by means of model in MathCad. The most important source of information is real run of tractor set along the plot.

From the results in Table 3 it is obvious, that electric drive of mulcher causes an increase in fuel consumption and production of emissions. It is caused above all by the fact, that it was used the tractor with combustion engine and only then there is attached to this combustion engine generator of electric energy. In case of electric drive of mulcher more devices is in operation, than in case of mechanical drive and therefore it decreases the efficiency of energy transfer. By this fact electric drive of mulcher is disadvantaged. In the model it was also calculated with the fact, that the reduction of mulcher rpm and also engine speed is possible both in case of mechanical drive and electric drive of mulcher. However it may not be true, especially in case of mechanical drive.

The average difference between the worst variant and the best variant, when we include both types of mulcher drive, makes approx. 40%. Three times there was achieved the best result by reduction of mulcher rpm (fuel consumption, NO_X, HC) and three times by reduction of mulcher rpm in combination with reduction of engine speed (CO_2, CO, PM). If this comparison will be related only to the electric drive of mulcher, it is possible to achieve by means of reduction of mulcher rpm, by reduction of combustion engine speed and by their combination the average reduction of fuel consumption and emissions by 15%. The greatest reduction was achieved in case of smoke by ca 40% and carbon dioxide by ca 25%.

The great potential of electric drive of mulcher and other agricultural machines can be seen in case of use of 100% electro-powered tractor without combustion engine. In this case the amount of produced emissions reaches only one third in comparison with mechanical drive of mulcher with inclusion of energy mix of the Czech Republic.

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