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Calculation model of the tractor transport set – Economic and environmental indicators

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Abstract: This contribution presents a calculation method of indicators in agricultural transport. The tractor Zetor Forterra 8641 with a silage trailer was used. Calculations were performed with various weights of transported material: 2.5, 3.6, 5.8, 7.4 and 9.0 tons. The model was created concerning significant parameters of the transport set, engine characteristics and route. It considered splitting of the route into elementary sections, in which important route parameters were regarded as constant. Indicators were defined in every section (fuel consumption, emissions, etc.) and overall values were calculated as a sum. The set with 7.4 t of load reached the lowest unit costs 20.62 CZK·tkm^{-1}, transport output 79.51 tkm·h^{-1} and unit consumption 0.14 L·tkm^{-1}. The set with the maximum load 9.0 t reached output 86.05 tkm·h^{-1} but unit costs were 20.68 CZK·tkm^{-1}. Using the maximum capacity was not the most effective option. When the weight of a load increased (from 2.5 to 9.0 t), driving time extended from 0.28 to 0.46 h and hourly transportation output increased from 38.60 to 86.05 tkm·h^{-1}, unit consumption decreased from 0.24 to 0.13 L·tkm^{-1}. Total emissions significantly increased, but unit emissions decreased in average two times for each pollutant.

Keywords: agricultural transport; fuel consumption; emissions; transport output; unit costs

Material transport and manipulation form are significantly important parts of production processes in agriculture (Syrový 2008). Any operation of transportation machines negatively affects the environment, mainly by gaseous and solid products of combustion.

This effect can be reduced by appropriate organization and precise process controlling. Generally, the amount of produced emissions is determined by fuel consumption, engine construction, its technical parameters and operational mode. The gaseous pollutants from diesel engine mainly contain hydrocarbons (HC), sulphur oxides (SO$_x$), nitrogen oxides (NO$_x$) and carbon-monoxide (CO) (Králik et al. 2016; Kuchar et al. 2017).

A basic assumption for effective agricultural transport in relation to the environment requires knowledge of energetic, exploitation, economic and environmental indicators. A calculation model is one of the solutions for management of indicators in agricultural processes (Syrový and Podpěra 2009) and serves as a decision support for using farming machinery (Søgaard and Sørensen 2004). The results shall be used also for determination of energy consumption and emissions production in transport (Dyer and Desjardins 2003).

When evaluating the agricultural transportation, it is necessary to consider its specific nature, characteristics and differences of transportation in various areas of agriculture. Typical characteristics are:

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short distances, mostly one-way utilization of transport (with and without the load), transportation of various materials, on-road and off-road conditions, seasonality and dependence on climatic conditions (Syrový 2008).

A fuel consumption and emissions are mainly influenced by technical parameters of transport (engine power, construction, weight, speed), characteristics of transported material and the route such as its length and incline, surface characteristic (solid road, dirt road, meadow etc.). Another factor is a driver – his or her driving skillset, psychological stress – mental load, discomfort in a cabin and fatigue (Kvíz and Kroulík 2017).

When determining the economic and environmental parameters of machinery utilization, different methods can be applied. Mimra et al. (2017) created an economic model for elimination of operational costs of the combine harvesters, using the simulated situations for risk analysis. Dependence of the fuel consumption on the engine rated power and its utilization was investigated by Grisso et al. (2008). Similarly, it is possible to determine a production of emission particles. Stationary load of the engine can be assumed to simplify calculations (Sahu and Raheman 2007; Kumar and Pandey 2009), however, it is preferable to take into account the changing (dynamic) load of the engine because this approach achieves more accurate results (Lindgren and Hansson 2004).

The most precise and effective operations are achieved when using controlled traffic farming and self-propelled machines together with automatic guidance systems (Bulgakov et al. 2018). In usual ways of transport, however, the parameters affecting indicators keep changing and the engine works in unstable temporal conditions. Therefore, our suggested calculation model considers splitting the route into particular sections, in which the parameters (such as surface quality, angles of curves, incline) were regarded as constant. The overall values of the whole route might be calculated as a sum of all sections.

Firstly, the aim of article is to summarize calculation possibilities of the environmental and economic indicators, using the tractor Zetor Forterra 8641 (Zetor, Czech Republic) and a silage trailer as the example. Secondly, the aim of article is to suggest a model of the transport process that will take into account the most significant parameters influencing economic and environmental indicators.

MATERIAL AND METHODS

A simplified scheme of the model is in Figure 1. It was developed in Visual Basic programming language (version VB 11.0). When we know the engine speed at the end of the previous section and at the beginning of following section, it is necessary to decide whether the speed gear should be switched (shift up or shift down). If yes, deceleration or acceleration of the set is performed considering the road difficulty. Zero power consumption is expected during the gear change (zero engine torque).

If shifting of gear is not necessary, the current speed of the set is compared with the required speed in the particular route section. Based on this comparison, it is determined whether the speed should be kept constant, accelerated or decelerated. Should the set slow down, then required deceleration and engine torque are selected. If the speed corresponds with the required speed, it is necessary to evaluate, whether there is enough engine power to keep this speed and determine appropriate torque and eventual deceleration (when power is too low). If acceleration is required, the accessible engine power is selected and acceleration is executed.

Finally, values of indicators are calculated in each section considering the acceleration (deceleration) of the set, the drive period and the change of set speed. The emissions production is given from the calculated values and input data.

The calculation process is repeated for each section of the route. Subsequently, indicators for the whole route are calculated as a sum.

Emissions production. The basic input data of the simulation model is dependence of emission production on engine speed and torque, i.e. so-called quantity surfaces. The example of characteristics measured for research on the tractor Zetor Forterra 8641 in co-operation of the Czech University of Life Sciences in Prague, Faculty of Engineering and Research Institute of Agricultural Engineering is shown in Figure 2 (Pexa et al. 2010). These characteristics were interpolated from 25 measuring points selected according to the engine data. During the measurement, engine was loaded by a hydraulic dynamometer attached to tractor's power take-off shaft and following values were recorded: engine speed, torque, fuel consumption and emission production.

Route description. The transportation route is defined by its length, elevation profile, characteristic of the surface and road curvature. The route

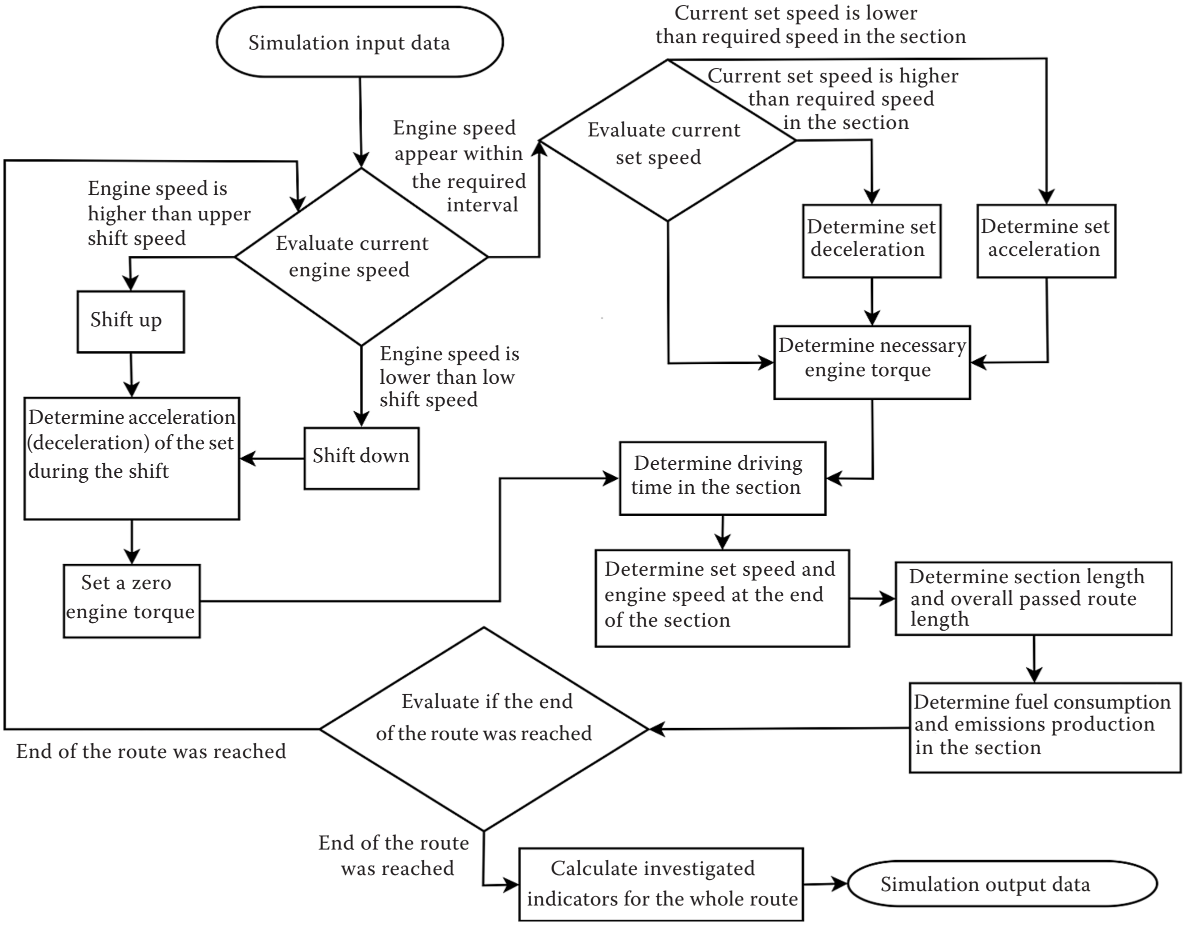

Figure 1. Simplified scheme of the calculation model

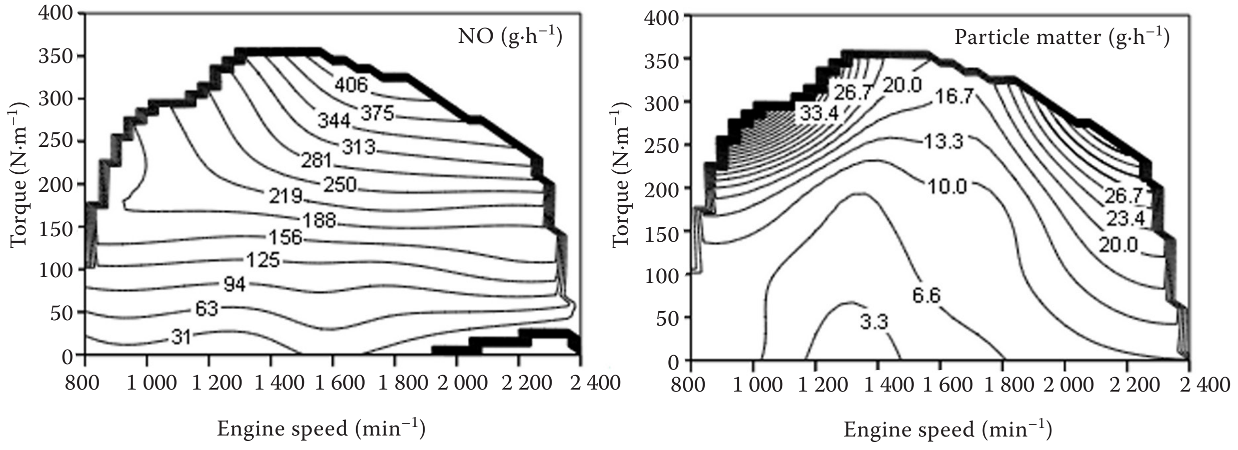

Figure 2. Quantity surface for (A) nitrogen oxide (NO) emissions and for (B) particle matter emissions (Zetor Forterra 8641 tractor)

is described with the use of the sequence of points that are determined by geographic coordinates (latitude, longitude and altitude), for example by GPS or by a digital map, which contains altitude terrain layers. The distance between measured points should enable to consider values within one section as constant.

Engine operating mode. It is necessary to determine the engine operating mode in each moment, to get correct calculation of the indicators. However, engine

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speed and torque continuously change during the operation and that is hard to simulate on PC using Visual Basic. The continuous function was changed into a discrete function, because constant values of engine speed and torque during short time sequences were expected. The operating mode of the engine was recorded in average 3 times per second.

Engine revolutions and their determination. Engine revolutions of the set at speed v_s can be calculated by Equation (1) (assumption: engaged clutch, which does not slip):

$$n_M = \frac{30 \times v_s \times i_c}{(1-\delta) \times \pi \times r_d} \tag{1}$$

where: n_M – engine speed (min^{-1}); v_s – actual speed of the transport set (m·s^{-1}); r_d – dynamic radius of drive wheels (m); i_c – total gear ratio between the engine and the drive wheels (–); δ – the slippage of drive wheels of the tractor (–).

The slippage of drive wheels of the tractor depends on the ratio between the driving force and the wheel vertical load and then on the characteristic of the surface and the tyre (Juostas and Janulevičius 2008). The intensity of the driving forces and surface characteristic changes during the drive, and therefore the slippage changes as well.

Engine torque determination. Torque is determined by current driving force, gear ratio between the engine and driving wheels and by transmission efficiency. The current torque shall be calculated according to the following Equation (2) (Bauer 2006).

$$M_M = \frac{F_h \times r_d}{i_c \times n_M} \tag{2}$$

where: M_M – engine torque (N·m^{-1}); F_h – driving force (N); h_m – transmissions efficiency between engine and driving wheels (–).

Driving force F_h of the wheels of the tractor is defined by Equation (3) has to overcome a resistance against the set movement, including F_f rolling resistance (N), F_v air resistance (N), F_s slope resistance (N), F_a inertial force (N) and F_t pull force (N).

$$F_E = F_f + F_v + F_s + F_a + F_t \tag{3}$$

In case of a complete transport set, the pull force F_t represents drive resistance of an trailer. (Syrový 2008).

Acceleration of the transport set in a route section. For simplification of the model it is assumed, that the current engine operating point is at the full load characteristics of the engine. Available acceleration of the set is calculated by Equation (4).

$$a = \frac{\dfrac{M_{Mmax} \times i_c \times n_M}{r_d} - F_f - F_v - F_s - F_t}{m_s + m_{red}} \tag{4}$$

where: M_{Mmax} – the maximal engine torque at current engine speed (N·m^{-1}).

Acceleration of the transport set varies with increasing speed due to changes of maximum engine torque with the engine speed. For the proposed model is average acceleration defined by Equation (5).

$$a_{avg} = \frac{a_p + a_k}{2} \tag{5}$$

where: a_{avg} – average acceleration of the set in the section (m·s^{-2}); a_p – the acceleration of the set on the beginning of the section (m·s^{-2}); a_k – the acceleration of the set on the end of the section (m·s^{-2}).

The engine speed difference between the start and the end of an section Δ*n* is entered as one of the data inputs. Engine speed difference Δ*n* ranges from 10 to 50 rpm seems to be an appropriate value for this model.

Route section – its length and driving time. The driving time of the set through a particular section and the length of this section can be determined by Eqautions (6) and (7).

$$\Delta t = \frac{v_k - v_p}{\bar{a}} \tag{6}$$

$$\Delta s = v_p \times \Delta t + \frac{1}{2} \times a_{avg} \times \Delta t^2 \tag{7}$$

where: Δ*t* – driving time through the section (s); Δ*s* – section length (m); v_p – set speed at the beginning of the section (m·s^{-1}); v_k – set speed at the end of the section (m·s^{-1}).

If the acceleration is too low, there could arise a situation, when the driving time through the section and mainly the length of the section could get too long and it would not be possible to consider basic parameters (slope angle, surface characteristics) as constant. Therefore, it is necessary to maintain appropriate speed and acceleration.

Calculation of the emissions production and fuel consumption. The emissions production depends on the current operation mode of the engine,

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i.e. on its speed and torque. If the tabulation values – quantity surfaces of the emissions production are known, then is possible to determine the emissions production in every operating point of the engine, with the use of an appropriate interpolation function. The relevant emission component production can be defined in every section by Equation (8).

$$E_x = \frac{E_{x,p} + E_{x,k}}{2} \times \frac{\Delta t}{3600} \quad (8)$$

where: E_x – production of the emission particle x in the section (g); $E_{x,p}$ – hourly production of the emission component x at the beginning of the section (g·h^{-1}); $E_{x,k}$ – hourly production of the emission component x at the end of the section (g·h^{-1}).

Transport in the area of agriculture shall be characterized mainly as a one-way operation. For this reason the investigated indicators are expressed for the whole transport cycle (driving with and without the load).

RESULTS AND DISCUSSION

Transportation of the forage in mountains was chosen for the validation of suggested calculation method. The simulated transport set consisted of the tractor Zetor Forterra 8641 (its quantity surfaces were stated in Figure 2) and the silage trailer. The calculation was done for various weights of a load on the trailer, from 2.5 up to 9 tons.

The route represented the real route in the mountainous area of Šumava, from a meadow near the village Úbislav to the area of an agricultural company in the village Nicov (altitude profile of the route is in Figure 3). Length of the route was 4.37 km.

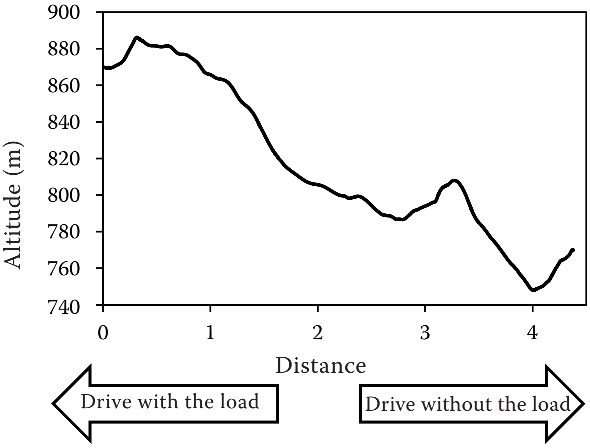

Figure 3. Altitude profile of the route

Results for the set with the weight of loaded material from 2.5 t to 9.0 t are presented in Figures 4, 5 and 6. Table 1 shows values for the overall consumption, overall driving time, overall emissions production and overall costs of the transportation cycle. Fundamental data for determination of the unit costs of a transportation cycle are overall driving time and hourly transportation output and the equation shall be stated as follows:

$$C_U = \frac{C_T}{O_T \times t_{rd}} \quad (9)$$

where: C_U – unit costs of the set (CZK·tkm^{-1}); C_T – the total costs (CZK); O_T – hourly transportation output (tkm·h^{-1}); t_{rd} – real driving time (hours).

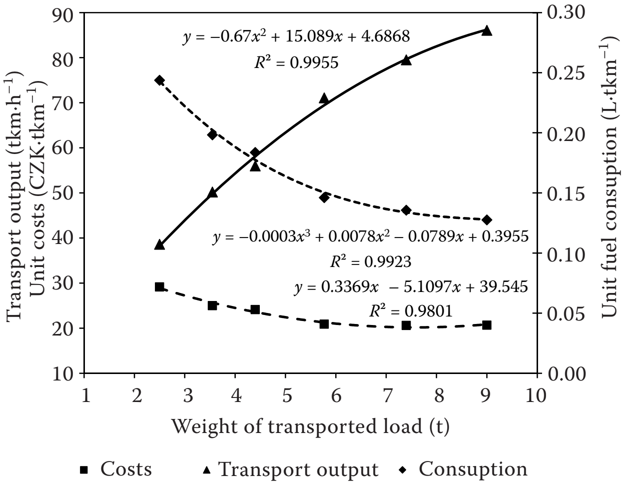

Figure 4. Dependence of transport output, fuel consumption and costs on weight of transported load

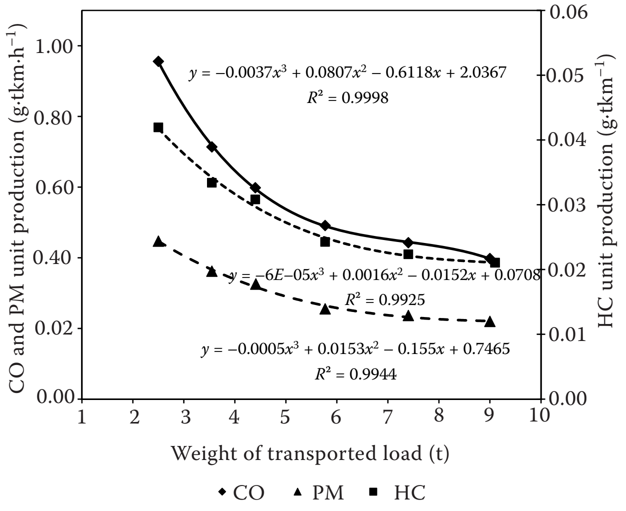

Figure 5. Dependence of carbon monooxide (CO), particulate matter (PM) and hydrocarbons (HC) unit production on weight of transported load

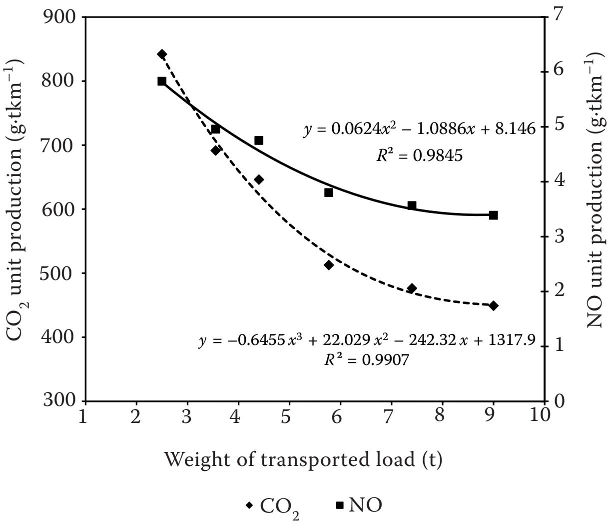

Figure 6. Dependence of CO_2 and nitrogen oxide (NO) unit production on weight of transported load

Minor deviations of the values are caused by rounding off the numbers to two decimal places.

Figures 7, 8, 9 and 10 show hourly production of PM (particulate matter) and NO_x during the route for the set with the weight of a load 2.5 and 7.4 tonnes. Dependence of PM and NO_x on the route profile may be observed. PM and NO_x were chosen to demonstrate the tendencies in this simulation.

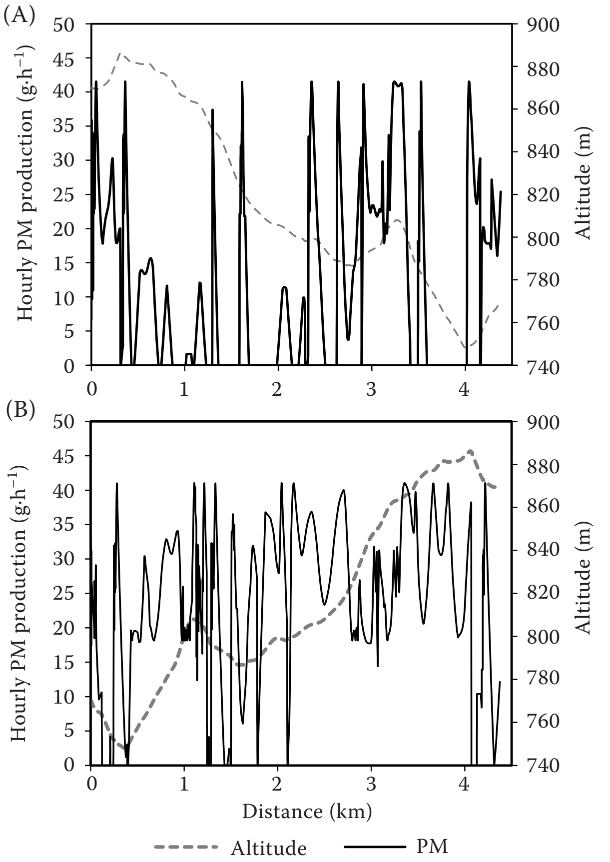

Figure 7. Hourly production of particulate matter (PM) (A) without the load and (B) the set with 2 500 kg load

Table 1. Calculated indicators of the transport set for different weights of transported load (for the whole transport cycle)

Indicators	Transported load (t)				
	2.5	3.6	5.8	7.4	9.0
Overall consumption (L)	2.67	3.08	3.69	4.39	5.03
Unit consumption (L·tkm^{-1})	0.24	0.20	0.15	0.14	0.13
Overall driving time (h)	0.28	0.31	0.36	0.41	0,46
Hourly transport output (tkm·h^{-1})	38.60	50.21	71.08	79.51	86.05
Total costs (CZK)	318.94	388.56	527.56	667.34	814.65
Unit costs of the set (CZK·tkm^{-1})	29.15	24.99	20.88	20.62	20.68
Total emission of CO (g)	10.46	11.09	12.41	14.34	15.67
Unit emission of CO (g·tkm^{-1})	0.96	0.71	0.49	0.44	0.40
Total emission of CO_2 (g)	9 214.79	10 748.52	12 950.32	15 431.45	17 699.01
Unit emission of CO_2 (g·tkm^{-1})	842.03	691.67	512.73	476.38	449.25
Total emission of HC (g)	0.46	0.52	0.61	0.72	0.83
Unit emission of HC (g·tkm^{-1})	0.04	0.03	0.02	0.02	0.02
Total emission of PM (g)	4.89	5.63	6.45	7.66	8.66
Unit emission of PM (g·tkm^{-1})	0.45	0.36	0.26	0.24	0.22
Total emission of NO (g)	63.79	77.03	96.02	115.48	133.49
Unit emission of NO (g·tkm^{-1})	5.83	4.96	3.80	3.57	3.39

CO – carbon monooxide; CO_2 – carbon dioxide; HC – hydrocarbons; PM – particulate matter; NO – nitrogen oxide

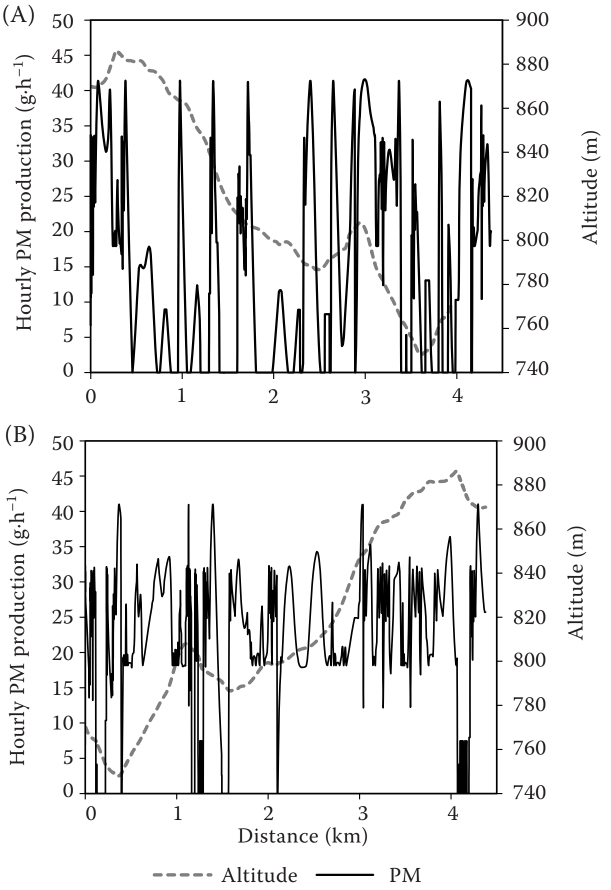

Figure 8. Hourly production of particulate matter (PM) (A) without the load and (B) the set with 7 400 kg load

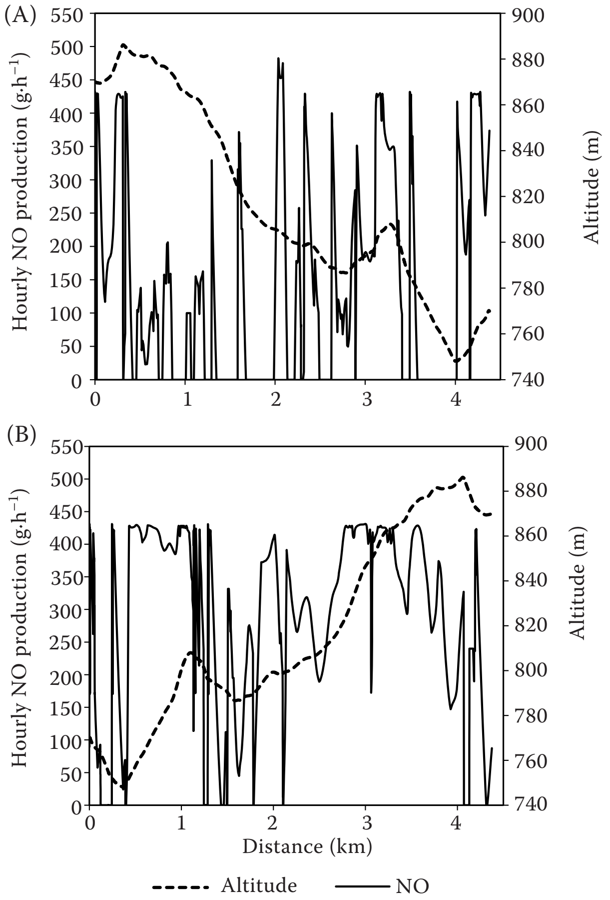

Figure 9. Hourly production of nitrogen oxide (NO) (A) without the load and (B) the set with 2 500 kg load

The results showed the expected tendency of the transport output of the set, which increased together with the weight of transported load. On the other hand, the unit fuel consumption and the unit emissions production decreased. The set with the weight of load 2.5 t performed the hourly transport output 38.60 tkm·h^{-1}, the unit consumption 0.24 L·tkm^{-1} and unit costs 29.15 CZK·tkm^{-1}. The unit production of single emissions components is 0.96 g·tkm^{-1} of CO, 842.03 g·tkm^{-1} of CO_2, 0.04 g·tkm^{-1} of HC, 0.45 g·tkm^{-1} of PM and 5.83 g·tkm^{-1} of NO. On the other hand, the set with the weight of a load 7.4 t reached the transport output 79.51 tkm·h^{-1}, while the unit consumption is only 0.14 L·tkm^{-1} and the unit costs are 20.62 CZK·tkm^{-1}. The unit production of single emissions components of the set with the weight of a load 7.4 t, is 0.44 g·tkm^{-1} of CO, 476.38 g·tkm^{-1} of CO_2, 0.02 g·tkm^{-1} of HC, 0.24 g·tkm^{-1} of PM and 3.57 g·tkm^{-1} of NO. The transport set with the load 9.0 t had the lowest unit fuel consumption 0.13 L·tkm^{-1} and hourly transport output 86.05 tkm·h^{-1}. However, the total cost while transporting 9.0 t were so high that unit costs reached 20.68 CZK·tkm^{-1}. From the results is obvious that maximum load was not the most optimal solution for this transport cycle. Generally, values of the total emissions increased for all pollutants, but the values of unit emissions decreased in average two times. The costs reached the minimum price with the weight of load at 7.4 tonnes (Figure 4).

Some authors published comparable studies, for example Polcar et al. (2016) calculated fuel consumption and transportation output dependent on engine power setting. Driving cycles were created to simulate real traffic and allow comparison of only some specific values, even with different methodology, units and machinery. NRSC and NRTC tests (Ettl et al. 2018) are used for tractors. Traction forces in connection with terramechanics was researched (Cutini and Bisaglia 2016), as well as the emissions and fuel consumption during real driving (Ince and Güler 2020) or during dynamometer simulation (Schlosser et al. 2017). Souček et al. (2017) published research focused

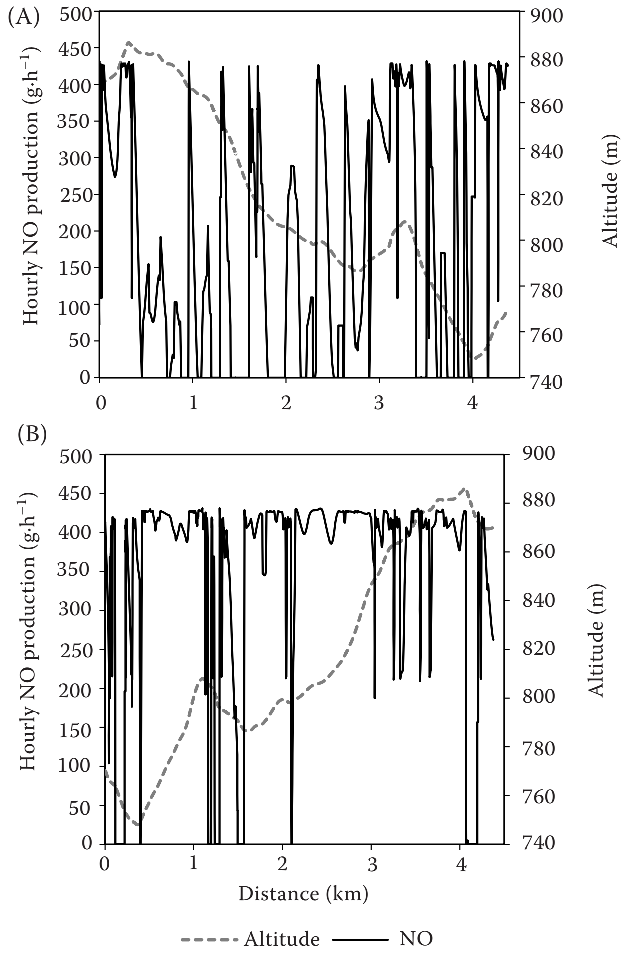

Figure 10. Hourly production of nitrogen oxide (NO) (A) without the load and (B) the set with 7 400 kg load

on importance of logistic, energy and exploitative parameters for the use of compost and manure from the viewpoint of transport and application in real operating conditions. The transport distance was 4.1–4.9 km and the weight of transported material 4.74–6.25 t, so that the conditions are comparable. From accessible results, specific fuel consumption and transportation output might be compared. Specific fuel consumption for transportation reached 0.303 L·tkm^{-1} and 0.278 L·tkm^{-1}, whereas our research claims consumption in interval 0.24–0.13 L·tkm^{-1}. Average transport output reached 88.45 tkm·h^{-1} and 102.00 tkm·h^{-1} whereas ours hourly transportation output was in interval 38.60–86.05 tkm·h^{-1}. Research of Souček et al. (2017) was not calculated with different weights of load and we do not have any information about the engine and route profile and this might have caused the differences. The specific fuel consumption is also mentioned in publication of Syrový (2008) who claimed optimal specific consumption during the transport at the value of 0.254 L·tkm^{-1}, which is comparable to our fuel consumption 0.24 L·tkm^{-1} with the maximum load. Syrový and Podpěra (2009) published theory of simulation mathematical model, similar to this one, which suggests very complex results (directs costs, material consumption, manpower need, etc.). It supports the methodology of this study.

CONCLUSION

The example of the calculation was applied on the tractor Zetor Forterra 8641 tractor with the silage trailer. The calculation was performed for 5 different wights of transported load on the trailer: 2.5, 3.6, 5.8, 7.4 and 9 tons. The dependence of investigated indicators on weight of the set was determined. The conclusions from presented results are following:

(*i*) When the weight of a load on the transport set increased from 2.5 to 9.0 t, driving time extended from 0.28 to 0.46 h and hourly transportation output increased from 38.60 to 86.05 tkm·h^{-1}.

(*ii*) The unit consumption decreased almost twice, from 0.24 to 0.13 L·tkm^{-1}.

(*iii*) The total (cumulative) emissions (CO, CO_2, HC, NO_x and PM) increased for all pollutants with increasing weight, but the unit emissions were reduced in average two times, presented in Figures 5 and 6.

(*iv*) The calculation of unit costs showed that the transport set works the most effectively with the load of 7.4 t when the unit costs reached 20.62 CZK·tkm^{-1}.

The calculation method may serve either for a determination of an appropriate set for a particular transport operation, but mainly for a simulation of indicators without a need to carry out difficult field-laboratory tests. Eventually, to set an amount of emissions produced during transport operations.

REFERENCES

Bauer F., Sedlák P., Šmerda T. (2006): Traktory. Prague, Profi Press.

Bulgakov V., Adamchuk V., Nozdrovický L., Kuvachov V. (2018): Study of effectiveness of controlled traffic farming system and wide span self-propelled gantry-type machine. Research in Agriculture Engineering, 64: 1–7.

Cutini M., Bisaglia C. (2016): Development of a dynamometric vehicle to assess the drawbar performance of highpowered agricultural tractors. Journal of Terramechanics, 65: 73–84.

Dyer J. A., Desjardins R. L. (2003): Simulated farm fieldwork, energy consumption and related greenhouse gas emissions in Canada. Biosystems Engineering, 85: 503–513.

Ettl J., Bernhardt H., Pickel P., Remmele E., Thuneke K., Emberger P. (2018): Transfer of agricultural work operation profiles to a tractor test stand for exhaust emission evaluation. Biosystems Engineering, 176: 185–197.

Grisso R.D., Vaughan D.H., Roberson G.T. (2008): Fuel prediction for specific tractor models. Applied Engineering in Agriculture, 24: 423–428.

Juostas A., Janulevičius A. (2008): Investigation of tractor engine power and economical working conditions utilization during transport operation. Transport, 23: 37–43.

Králik M., Jablonický J., Tkáč Z., Hujo Ľ., Uhrinová D., Kosiba J., Tulik J., Záhorská R. (2016): Monitoring of selected emissions of internal combustion engine. Research in Agricultural Engineering, 62: S66–S70.

Kuchar P., Halenár M., Hajdák V. (2017): Technical-economic analysis and evaluation of transport organization. In: Proceedings of the 19th International Conference of Young Scientists. Prague, Sep 13–14, 2017: 116-121.

Kumar R., Pandey K.P. (2009): A program in Visual Basic for predicting haulage and field performance of 2WD tractors. Computers and Electronics in Agriculture, 67: 18–26.

Kvíz Z., Kroulík M. (2017): Automatic guidance systems in agricultural machinery as a tool for drivers' mental strain and workload relief. Research in Agricultural Engineering, 63: S66–S72.

Lindgren M., Hansson P.A. (2004): Effects of transient conditions on exhaust emissions from two non-road diesel engines. Biosystems Engineering, 87: 57–66.

Ince E., Güler M.A. (2020): On the advantages of the new power-split infinitely variable transmission over conventional mechanical transmissions based on fuel consumption analysis. Journal of Cleaner Production, 244: 118795.

Mimra M., Kavka M., Kumhála F. (2017): Risk analysis of the business profitability in agricultural companies using combine harvesters. Research in Agricultural Engineering, 63: 99–105.

Pexa M., Kubín K., Novák M., Pošta J. (2010): Fuel consumption and emissions of tractor Zetor Forterra 8641. Acta Technologica Agriculturae, 13: 79–82.

Polcar A., Vít M., Čupera J. (2016): Possibilities to reduce operating costs in transport of agricultural crops. Sugar and Sugar Beet Journal, 132: 230–233.

Sahu R.K., Raheman H. (2007): A decision support system on matching and field performance prediction of tractor-implement system. Computers and Electronics in Agriculture, 60: 76–86.

Schlosser J.F., de Farias M.S., Estrada J.S., dos Santos G.O., Gil E. (2017): Performance and emission of pollutants of an agricultural engine with two power take-off settings. Engenharia Agricola, 37: 277–285.

Souček J., Pražan R., Roy A., Plíva P., Jelínek A., Vegricht J. (2017): Comparison of logistic, energy and exploitative parameters of compost and manure application by spreaders. Research in Agricultural Engineering, 63: S33–S39.

Søgaard H.T., Sørensen C.G. (2004): A model for optimal selection of machinery sizes within the farm machinery system. Biosystems Engineering, 89: 13–28.

Syrový O. (2008): Doprava v Zemědělství. Prague, Profi Press.

Syrový O., Podpěra V. (2009): Simulation mathematical model of expert system for working processes management. Research in Agricultural Engineering 55: 1–9.

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