Optimisation of a clam bunk skidder from the emission production point of view

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Abstract

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This article presents a proposal of a simple mathematical model for minimisation of the production of extraneous substances as a function of the rate of operation performance of a production system. The model is then verified by operation tests of the Terri 2040 clam bunk skidder and by determining the system's optimal rate of performance from the point of view of production of SO_2, HC and NO_x emissions. The operation tests conducted to verify the mathematical model have confirmed that conditions can be determined for the production system at which it produces minimum emissions. Min. values of SO_2, and HC were achieved at approximately the same rate of performance of the clam bunk skidder. Minimum values of NO_x were achieved at significantly higher rate of performance of the equipment. At the calculated optimal rate of operating performance of the Terri 2040 clam bunk skidder, the values of the produced emissions were determined per m^3 of timber: SO_2 = 1.00035 g/m^3, HC = 7.796 g/m^3 and NO_x = 0.277 g/m^3.

Keywords: mathematical model; production system; combustion engine; rate of performance; emission; sulphur dioxide; unburned hydrocarbons; nitrogen oxides

Imperfect combustion of motor fuels results in the production of undesirable, to a larger or lesser degree harmful components. The main products of imperfect combustion are carbon dioxide, carbon monoxide, nitrogen oxides, sulphur dioxide, unburned hydrocarbons and solid particles. The Euro V Emission Standards applicable in the European Union member states set limit values of exhaust exhalations of diesel engines for NO_x, HC, CO and solid particles. Other monitored emission components are SO_2, CO_2 and Pb. In this article we will analyse the production of SO_2, HC and NO_x emissions in relation to the production system's rate of performance.

Sulphur oxides are produced especially by diesel engines. And it is sulphur dioxide (SO_2), which is dangerous, because it reacts with water and forms sulphuric acid which results in so called acid rain. When the engine is running unloaded, or when the air surrounding the engine cylinders cools down, unburned hydrocarbons (HC), are generated, which were only partially oxidised during the combustion process. This results in emissions being produced which are predominantly carcinogenic. Nitrogen oxides (NO_x), which in the combustion of motor fuels consist mainly of nitrogen monoxide (NO) and nitrogen dioxide (NO_2), are a major con-

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tributor to the summer smog and acid rain. Nitrogen monoxide is particularly harmful, as it forms nitric acid.

Numerous papers dealing with the issues of reducing emissions of internal combustion engines have been published. However, none of them dealt with the issues of minimising the emissions of forestry logging machinery and systems. Swedish scientists (Linholm et al. 2010) studied in seven different localities energy input-to-output ratios and CO_2 emissions during the operations of removing stumps and waste produced in logging operations. The results of the study showed that the ratio of the energy contained in the stumps and waste generated in logging operations to the energy consumed in the logging operation varied between 21 and 48. Emissions of CO_2 equivalent reached the values between 1.5 and 3.5 g/MJ of the energy obtained. The authors pointed out at the necessity of developing a technology to be deployed in stump logging operation and collection of waste generated in logging operations. Klváč and Skoupý (2009) presented the results of monitoring the emissions generated by eight clam bunk skidders and rigs with the engine output 70.8–156.6 kW. They defined the relationship between the engine's output and fuel consumption. They calculated exhaust fume emissions from average values of diesel fuel and rape methyl ester (RME) consumption by means of correlation and regression models. The results showed that CO_2 emissions amounted to 9.63 and 10.64 kg/m^3 for diesel and rape methyl ester (RME), respectively. The authors claim that when rape methyl ester (RME) is used, only 2.82 kg/m^3 of CO_2 emissions originates from fossil fuels, and hence consider only this amount to be an ecological burden polluting the surrounding environment. Swedish researchers Hansson and Mattsson (1999) monitored emissions produced by a tractor of 70 kW output in wheat growing work operations. In the first stage of the works they measured and computed emissions in individual work operations. In the second stage they compared their measurements and computations with the values traditionally used in emission calculations. The results of these comparisons showed that the newly acquired data concerning the production of HC, CO, NO_x and SO_2 in the chain of wheat growing work operations were significantly lower than what was hitherto believed. Another conclusion they arrived at was that the emission production depends on the type of work operation, but also how it is carried out. In France Chauvet et al. (2010) proposed a methodology of computing greenhouse gases generated in logging, skidding and transportation operations. They applied the methodology in the French region of Auvergne. The results of their monitoring showed that average total quantity of greenhouse gases generated in logging, skidding and transportation operations amounted to 4.676 kg of CO_2 equivalent. They then proposed 32 measures to reduce the generation of greenhouse gases in the forestry industry. One of the recommendations was an optimal rate of machine performance. Berg and Lindholm (2005) give as a total consumption of energy required to produce 1 m^3 of timbre, including nursing seedlings, logging, skidding, transportation and other work operations in the value of 150–200 MJ/m^3, whereby most of the energy is consumed in secondary transportation. The results of this monitoring which lasted several years showed that the emissions of CO_2, SO_2, HC as well as NO_x produced it; the actual logging operations were significantly lower than ten years earlier. The reason for this drop in the production of emissions is a better design of current machinery and equipment, combined with optimised logging operations from the rate of operation performance point of view.

The aim of our studies was to construct a simple mathematical model formulating minumum emissions of SO_2, HC and NO_x as a function of the production system's rate of performance, and to verify this model in the operation of the Terri 2040 (THT A. B., Morgongåva, Sweden) clam bunk skidder.

MATERIAL AND METHODS

For any production system to function, energy, material and labour must be supplied. When the production system is working, this energy and material are irreversibly transformed and the resultant product is created. An accompanying characteristic phenomenon of the irreversible transformation of energy is dissipative energy which manifests itself by increased entropy. The generated dissipative energy is a carrier of emissions of extraneous substances which have a negative impact on the environment. The production of emissions of extraneous substances is a function of work intensity, i.e. the production system's rate of performance. These emissions, generated in the production system as a consequence of the energy transformation, can be expressed by the following Eqs (Janeček 1996):

$$M_E = \frac{m_E \times q_E}{\eta_{CE}} s_E \qquad \text{(kg)} \qquad (1)$$

$$M_E^l = \frac{\frac{\partial m_E}{\partial t} \times q_E}{\eta_{CE}} s_E \qquad \text{(kg/s)} \qquad (2)$$

where:

M_E – emissions produced by the production system (kg)
m_E – quantity of energy carrier entering the production system (kg)
q_E – specific energy of the energy carrier (kJ/kg)
η_{CE} – rate of performance of energy transformation (–)
s_E – specific inherent production of emissions (kg/kJ)
t – time (s)
M_E^l – total emissions produced by the production system per unit of time (kg/s)
$\partial m_E/\partial t$ – quantity of energy carrier entering the production system per unit of time (kg/s)

The following relationship applies to specific emission Q_E per unit of the rate of performance:

$$Q_E = \frac{M_E^l(W_k, W_p)}{W(W_k, W_p)} \qquad \text{(kg/m}^3\text{)} \qquad (3)$$

where:

W_p – rate of operation performance of the production system (m^3/s)
W_k – rate of design performance of the production system (m^3/s)
$W(W_k, W_p)$ – total rate of performance of the system as a function of W_k and W_p
$M_E^l(W_k, W_p)$ – total emissions produced by the production system per unit of time as a function of W_k and W_p (kg/s)

The following relationships apply to extremes of the function of specific emission Q_E per units of the performance rate W_k and W_p:

$$\frac{\partial Q_E}{\partial W_k} = 0 \qquad (4)$$

$$\frac{\partial Q_E}{\partial W_p} = 0 \qquad (5)$$

In the above relationships, in respect of the function of specific emission per unit of performance, we consider the rate of design and operation performance to be variables. By applying partial derivation to the function of specific emission as a function of the rate of design and operation performance $Q_E(W_k, W_p)$ by W_k and W_p, after adjustments we obtain the following expressions which define the minimum functions of specific emission $Q_E(W_k, W_p)$:

$$\frac{\partial Q_E}{\partial W_p} = \frac{\frac{\partial M_E^l(W_k, W_p)}{\partial W_p} \times W(W_k, W_p) - M_E^l(W_k, W_p) \times \frac{\partial W(W_k, W_p)}{\partial W_p}}{\left[W(W_k, W_p)\right]^2} = 0 \qquad (6)$$

$$\frac{\partial Q_E}{\partial W_k} = \frac{\frac{\partial M_E^l(W_k, W_p)}{\partial W_k} \times W(W_k, W_p) - M_E^l(W_k, W_p) \times \frac{\partial W(W_k, W_p)}{\partial W_k}}{\left[W(W_k, W_p)\right]^2} = 0 \qquad (7)$$

By adjusting the above Eqs into an implicit expression for optimal rate of performance $W(W_k, W_p)$ in the function of the rate of design and operation performance, we get:

$$W_{\text{opt},k} = \frac{M_E^l(W_k, W_p) \times \frac{\partial W(W_k, W_p)}{\partial W_k}}{\frac{\partial M_E^l(W_k, W_p)}{\partial W_k}} \qquad \text{(m}^3\text{/s)} \qquad (8)$$

$$W_{\text{opt},p} = \frac{M_E^l(W_k, W_p) \times \frac{\partial W(W_k, W_p)}{\partial W_p}}{\frac{\partial M_E^l(W_k, W_p)}{\partial W_p}} \qquad \text{(m}^3\text{/s)} \qquad (9)$$

These expressions for an optimal rate of performance do not have an analytical solution, these are used in the processors installed in production systems, where they automatically compute an optimal work solution from the point of view of the set criteria, in our case partial emissions of extraneous substances.

By solving the above expressions, we obtain Eqs which allow us to express the rate of operation performance at which the production system will produce min. emissions, i.e. the rate of performance at which min. dissipative energy will be generated.

The above mathematical formulations of production system's behaviour were tested in the operation of the Terri 2040 clam bunk skidder. This clam bunk skidder comprises of a caterpillar tractor with hydro-mechanical drive, a hydraulic crane and a trailer. The rig is used to manipulate and skid logs of 2 to 4 m length.

Basic technical parameters of the Terri 2040 clam bunk skidder:

– Kubota D 1105 engine (Kubota Corporation, Osaka, Japan)
  1,124 cm^3, diesel, 4-stroke, 3-cylinder,
  17.6 kW (24 HP) at 3,000 rpm
– maximum torque 73 Nm at 2,000 rpm
– crane reach 7.0 m
– crane load capacity 4,316 N
– total weight 4,950 kg

– transportation weight 2,960 kg

The Terri 2040 clam bunk skidders on a caterpillar chassis with their very low pressure on the ground are regarded in the forestry industry as work machines with minimised negative impact on the environment. They are used in the Šumava National Park, Krkonoše Mountains and other protected territories (in the Czech Republic??).

Diesel fuel consumption of the Terri 2040 clam bunk skidder as a function of the rate of operation performance was determined by measuring the level of fuel in the tank with a dipstick. Following the diesel consumption determination, emissions of gaseous noxious substances SO_2, HC and NO_x in exhaust fumes were determined in relation to the permissible limiting values specified by the UNECE Regulation No. 49 (EURO 4) and corresponding Directive 1999/96/EC. (nejsou v references)

RESULTS AND DISCUSSION

The graph in Fig. 1 illustrates the results of monitoring diesel consumption as a function of the Terri 2040 clam bunk skidder's rate of performance.

An increase in diesel consumption N as a function of the clam bunk skidder's rate of performance W_p can be expressed by the following equation:

$$N = 5.07 \times 10^{-4} W_p^2 - 6.21 \times 10^{-3} W_p + 180 \quad (R^2 = 0.583)\ (\text{l}) \qquad (10)$$

The graphs at Fig. 2 illustrates the results of monitoring the production of emissions of SO_2, HC and NO_x by the Terri 2040 clam bunk skidder in operation. The horizontal axes of the graphs show the equipment's rate of operation performance W_p (m^3/month), and the left side vertical axes monthly production of emissions (SO_2, HC, NO_x) (kg/month). The right side vertical axes show specific production of emission (SO_{2m}, HC_m, NO_{xm}) (g/m^3) per m^3 of timber logged.

The monthly production of emissions as a function of the clam bunk skidder's rate of performance increases according to the following equation:

$$SO_2 = -9 \times 10^{-11} W_p^3 + 6 \times 10^{-7} W_p^2 + 9 \times 10^{-6} W_p + 0.467 \quad (R^2 = 0.999)\ (\text{kg/month}) \qquad (11)$$

$$HC = 2 \times 10^{-10} W_p^3 + 4 \times 10^{-7} W_p^2 + 0.005 W_p + 1.26 \quad (R^2 = 0.999)\ (\text{kg/month}) \qquad (12)$$

$$NO_x = 5.87 \times 10^{-11} W_p^3 - 2.26 \times 10^{-7} W_p^2 + 4.86 \times 10^{-4} W_p - 0.019 \quad (R^2 = 1.0)\ (\text{kg/month}) \qquad (13)$$

Equations of the functions of the individual specific emissions look as follows:

$$SO_2 = -1.58 \times 10^{-13} W_p^3 + 7.26 \times 10^{-8} W_p^2 + 1.88 \times 10^{-4} W_p + 1.12 \quad (R^2 = 0.996)\ (\text{g/m}^3) \qquad (14)$$

$$HC = -8 \times 10^{-11} W_p^3 + 10^{-6} W_p^2 - 0.002 W_p + 9.949 \quad (R^2 = 0.965)\ (\text{g/m}^3) \qquad (15)$$

$$NO_x = -10^{-12} W_p^3 + 4 \times 10^{-8} W_p^2 + 10^{-4} W_p + 0.161 \quad (R^2 = 1.0)\ (\text{g/m}^3) \qquad (16)$$

Results of the measurements presented in the graph of Fig. 1 show that the TERRI 2040 clam bunker skidder when skidding 1 m^3 of timber over a skidding distance 154–731 m consumed 0.52–1.30 l of diesel fuel. This value roughly corresponds to the specific diesel fuel consumption arrived at by the Swedish researchers Berg and Lindholm (2005).

Fig. 2 shows that the values of production of the individual emissions per month of operation differ. The largest was production of unburned hydrocarbons (HC) which reached values 4.00 to 20.10 kg per month. The production of sulphur dioxide (SO_2) varied between 0.60 and 2.64 kg/month and the production of nitrogen oxides (NO_x) was relatively low at 0.22–0.52 kg/month. However, the production of NO_x was monitored only up to the rate of operation performance 2,000 m^3/month, whereas the production of other emissions were monitored up to the rate of performance 2,500 m^3/month.

The results of monitoring specific emissions as a function of the equipment's rate of performance, presented in the graphs of Fig. 2, show that there is always a minimum value of the specific emission which corresponds to a particular rate of operation performance. The French researchers Chauvet et al. (2010) who monitored the production of emissions during logging, skidding and transportation of timber in the Auvergne region, arrived at the same conclusion. And so did the Swedish researchers Hansson and Mattsson (1999), who determined the production of emissions in a chain of wheat growing work operations.

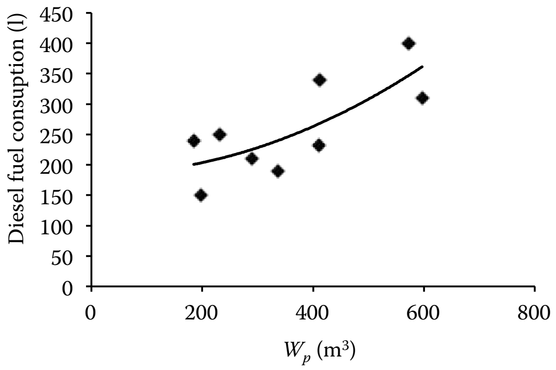
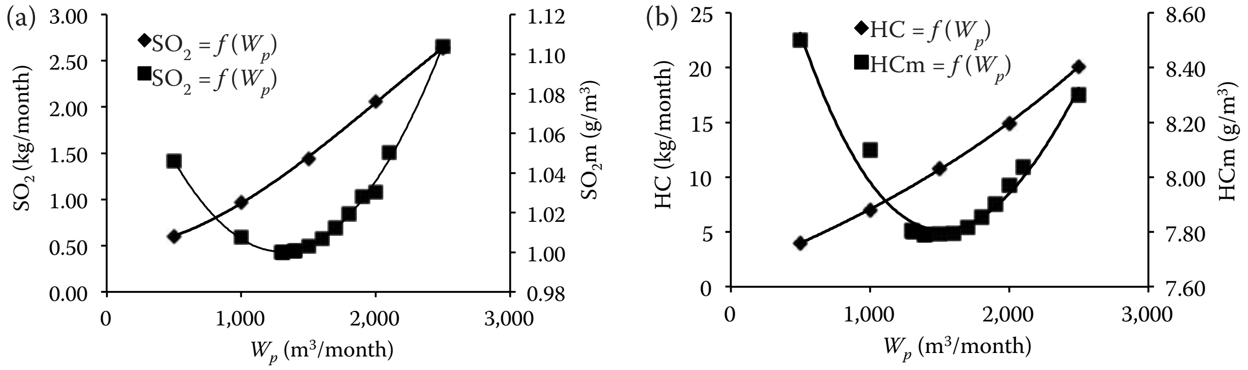


Fig. 1. Diesel fuel consumption as a function of clam bunk skidder's rate of performance



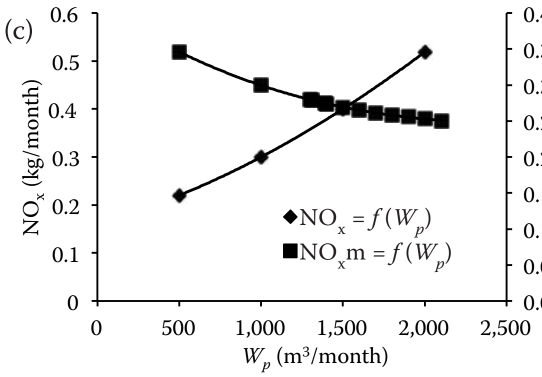


Fig. 2. Production of SO_2 (a), HC (b) and NO_x (c) emissions as a function of the clam bunk skidder's rate of performance

Changes in the rate of operation performance from the point of view of production of individual emissions are documented in the sensitivity analysis presented in Table 1. Table 1 shows minimum specific production of SO_2 = 1 g/m^3 at the clam bunk skidder's rate of operation performance W_p = 1,310 m^3/month, minimum specific production of HC = 7.79 g/m^3 at W_p = 1,390 m^3/month and min. specific production of NO_x = 0.25 g/m^3 at W_p = 2,100 m^3/month. These results show that the minimum specific productions of the three emissions were reached at three different rates of operation performance of the clam bunk skidder.

Table 1. Sensitivity analysis of emissions produced by TERRI 2040 clam bunker skidder as a function of the equipment's rate of performance

W_p (m^3/month)	SO_2	HC	NO_x
	minimum (g/m^3)		
	1.0	7.79	0.25
	deviation from minimum (%)		
1,300	0.02	0.19	11.97
1,310	0	0.16	11.74
1,390	0.07	0	9.90
1,400	0.08	0.01	9.69
1,500	0.31	0.05	7.67
1,600	0.69	0.07	5.93
1,700	1.24	0.36	4.46
1,800	1.94	0.82	3.27
1,900	2.81	1.44	2.35
2,000	3.05	2.32	1.70
2,100	5.04	3.17	0

W_p – rate of operation performance of the production system

The optimum rate of operation performance from the point of view of production of SO_2 and HC emissions differs by a mere 5.75%. A min. production of NO_x is achieved at considerably higher rate of the equipment's performance. However, production of NO_x emissions is, due to the type of the diesel engine used, relatively slow. Hence we can regard as an optimum rate of operation performance from the point of view of all the monitored emissions, an average value between 1,310 and 1,390 m^3/month, i.e. 1,350 m^3/month. Then the production of emissions will be SO_2 = 1.00035 g/m^3, HC = 7.796 g/m^3 and NO_x = 0.277 g/m^3.

CONCLUSION

The results show that the design of the clam bunk skidder and its rate of operation performance have a significant impact on the production of emissions, i.e. primarily on the efficiency of the transformation of the input energy in the form of fuel (diesel). The results furthermore confirm the validity of the hypothesis presented at the beginning of this paper, that the value of dissipative energy, i.e. the energy lost due to irreversible transformation to a different kind of energy, can represent the degree of the machine or production system's impact on the environment. Verification of the mathematical model in operation confirmed that it is possible to define conditions which, if met, will lead to minimisation of emission production per unit of the production system's rate of performance.

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