Rationalization of the performance of a mobile off-road system working in the forest environment with respect to its emission load

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ABSTRACT: This paper deals with the possibilities of minimizing the emissions of heterogeneous substances/pollutants (SO_2, NO_x and NC_x) per volume unit of processed timber, based on measurements of the design and operating performance of a mobile off-road system working in the forest environment. The forest production system is taken to mean the production system into which the material and resource flow and/or even the workforce flow enter. During the production process the material, power and/or workforce flow is transformed into the final product (processed timber, soil preparation, afforestation, etc.). Operating and/or design capacity is the control variable optimizing the operating mode of the forest production system. The quantities of emitted pollutants related to the work unit done by the production system represent the criterional function specifying the optimization of parameters of the mobile off-road system working in the forest sector. The conditions for the operating mode (performance) of the mobile off-road system working in the forest environment under which the minimum emitted pollutants related to the unit of done work are reached have been determined. The theoretical conclusions have been verified experimentally.

Keywords: forest technology; SO_2, NO_x, NC_x; optimizing; minimization

Production processes used in the implementation of silvicultural and logging operations in forestry bring about large amounts of gaseous and liquid emissions of extraneous substances. Many of them cause the pollution of atmosphere and/or soil, surface and ground water (leakages of oils, fuels, etc.). The emissions particularly worsen the situation in forest stands endangered by air-pollution (Skoupý 2000).

The amount of emissions produced by forest technologies was studied by Athanasiadis (2000) and by Berg and Karjalainen (2003). The authors determined the amount of emissions by the consumption of fuels in the individual forest operations and by the specific emission factor of individual fuel types. Dias et al. (2007) published a method of assessing the amount of emissions based on fuel consumption and on effective work time both for motor-manual and fully mechanized logging and transport technology.

The engine adjustment including the injection timing, the injection pressure and the fuel pump plunger diameter to achieve the lowest possible emissions was studied by Lejny et al. (2006). The problem of injection timing adjustment was also solved by Parlak et al. (2005), who arrived at a conclusion

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that NO_x emissions could be effectively reduced by proper injection timing. The authors' focus was however the engine design.

None of the above-mentioned authors has been engaged with a possibility of affecting the amount of emissions through the regime of work or by using the technique of rational performance and by specifying the work regime at which emissions are the lowest. Only Berg and Lindholm (2005) studied a possibility of fuel-related (CO_2, SO_x) or engine-related (hydrocarbons, NO_x) emissions decreased by the use of renewable fuels and through the improvement of the engine design and better adjustment of engines designed for operations in the forest.

Nevertheless, should the machine (system) be already made, emissions can be optimized by its suitable rational performance. The most important measures compensating the environment contamination by extraneous substances are preventive measures that can be applied on a larger part of the area of endangered forest ecosystems. According to Janeček (1992), the measures consist in the selection of appropriate and environment-friendly technologies including the choice of suitable machinery, and in using acceptable methods for the employment of machines with the rational performance. Possibilities to determine the rational performance of machines are further discussed in this paper.

The objective of this paper was to present some results from the analysis and from the determination of mathematic conditions required for reaching minimum specific emissions from logging and transport operations in the forest in relation to extracted mass unit.

MATERIALS AND METHODS

The outline of deduction of the criterional function of specific heterogeneous substance emissions related to the timber yield volume unit was carried out in view of the objective mentioned above. Mathematical conditions for determination of the local extreme of the function of specific heterogeneous substance emissions were determined in dependence on the performance and physical significance of the terms of inequalities or equations specifying the above-mentioned extreme of specific heterogeneous substance emissions were expressed. The papers published by Janeček et al. (1991), Bellman (1956), Wiener (1954), Skoupý (2000) and Janeček and Mikleš (2003) represented the methodological basis.

Theoretical conclusions were verified experimentally by monitoring the emissions of a Swedish-made TERRI 20-40 forwarder.

Qualitative specification of factors affecting emissions of heterogeneous substances

Logging and transport systems of different design performance, reaching different specific amount of material consumption, are used in the field of forest management. The specific heterogeneous substance emissions are proportional to the different used systems.

Factors affecting specific resource and material consumption:
- The change in all assemblies of logging and transport systems affecting the consumption of resources, material and/or labour is not directly proportional to an increase in the design performance;
- The changed investment intensity of logging and transport systems is not proportional to the change in performance. Such a situation arises due to the use of different unified assemblies manufactured in different typified sizes, i.e. their use usually leads to a certain oversize;
- Dimensional changes in stages (material flows processed by the logging and transport systems), resulting from the changed performance of the system, do not always cause a change in power and material consumption and thus a change in heterogeneous substance emissions proportional to the changed performance, which is in general the function of material flow velocity and cross section.

When analyzing these effects in greater detail, not only the kind of the logging and transport system but also particularly the method of reaching its design performance have to be considered.

Possibilities of increasing the design performance of forest systems:
- Increased material flow range
  By increasing the number of working assemblies (e.g. cutting mechanisms – used particularly for silvicultural operations);
  By extending the working assembly (e.g. extension of the cutting mechanism length – cutter bars);
- By extending the cross sections within roads where the material is transported;
- By increasing the maximum working capacity (performance).

Determination of the optimum regime of the logging and transport system from the aspect of specific heterogeneous substance emissions related to the performance unit

Resources, material and/or workforce enter into the logging and transport system. Resources and

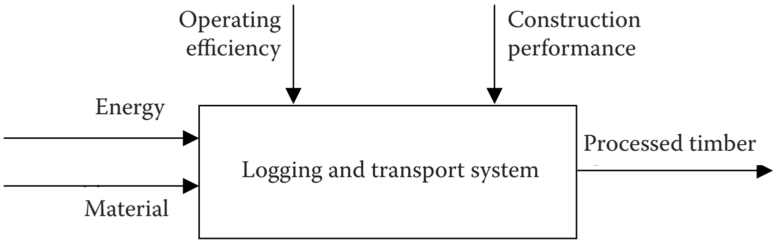

Fig. 1. Flow sheet of the logging and transport system

material are transformed during the production process, thus creating the resultant product, i.e. processed timber. The intensity of labour is controlled by the controllers specifying the design and operating performance (Fig. 1).

Emissions of heterogeneous substances, reflecting losses of energy during the process of production depend on the rate of work of the logging and transport system.

Janeček and Mikleš (2003) show that the following equation is valid for the expression of quantities of emissions of heterogeneous substances from timber logging and transport occurring due to energy transformation:

$$M_{EE} = \frac{m_E \times Q_E}{\eta_{CE}(W_K, W_P)} \times S_E(W_K, W_P) \quad \text{(kg)} \qquad (1)$$

where: M_{EE} – quantities of emissions from timber logging and transport generated by the work of the logging and transport system as a consequence of energy transformation (kg),
m_E – the quantity of energy resources (Diesel fuel, petrol) necessary for logging and production (kg),
W_p – the operating performance of the system (m^3/s),
W_k – the design performance of the system (m^3/s),
$S_E(W_p, W_k)$ – specific inherent emissions generated by energy and material transformation during the production process depending on design and operating performance (kg/kJ),
Q_E – the specific energy of the resource (kJ/kg),
$\eta_{CE}(W_k, W_p)$ – the efficiency of resource transformation into the resultant product depending on design and operating performance.

The following relation is valid for the total volume produced by the logging and transport system during the transformation of energy quantum Q_E

$$W_{CE} = \frac{m_E \times Q_E}{Q_V \times \eta_{CE}(W_K, W_P)} \quad (\text{m}^3) \qquad (2)$$

where: W_{CE} – the total production volume of the system produced due to energy transformation (m^3),
Q_V – the specific production energy which has to be supplied to the logging and transport system per unit of production (kJ/m^3).

The time derivations of equation (1) can be expressed in the following form, provided that the values Q_E, S_E and η_{CE} are constants for the analyzed time:

$$\frac{\partial M_{EE}}{\partial t} = \frac{\frac{\partial m_E}{\partial t} \times Q_e}{\eta_{CE}(W_K, W_P)} \times S_E \quad \text{(kg/s)} \qquad (3)$$

According to Janeček and Mikleš (2003) the following relation can be applied to quantities of heterogeneous substance emissions related to the performance unit of the mobile off-road system

$$Q = \frac{\partial M_{EE}}{\partial t} \times \frac{1}{W_C(W_K, W_P)} = \frac{\frac{\partial m_E}{\partial t} \times Q_E \times S_E}{\eta_{CE}(W_K, W_P)} \times$$

$$\times \frac{1}{W_C(W_K, W_P)} \quad (\text{kg/m}^3) \qquad (4)$$

where: Q – specific heterogeneous substance emissions generated per volume unit (kg/m^3),
t – the time (s),
$\frac{\partial M_{EE}}{\partial t}$ – the quantities of heterogeneous substance emissions from timber logging and transport per time unit generated as a consequence of energy transformation (kg/s),
$\frac{\partial m_E}{\partial t}$ – the quantities of resources supplied per time unit (kg/s).

The following equation is valid for the system performance

$$W_C = \frac{\partial W_{CE}}{\partial t} \quad (\text{m}^3/\text{s}) \qquad (5)$$

The necessary conditions shown below are valid for the extreme of the function of specific heterogeneous substance emissions, related to the volume unit of processed mass as the function of design and operating performance:

$$\frac{\partial^2 M_{EE}(W_K, W_P)}{\partial t \times \partial W_K} = 0 \quad (\text{kg/m}^3) \qquad (6)$$

$$\frac{\partial^2 M_{EE}}{\partial t, \partial W_p} = 0 \quad (\text{kg/m}^3) \qquad (7)$$

After realization of all operations as mentioned above and after modifications (Janeček, Mikleš 2003) we derive the expressions deciding the sign of partial derivations in the form

$$\frac{\partial f_E(W_K, W_P)}{\partial W_K} - \frac{f_E}{\eta_{CE}(W_K, W_P)} \times \frac{\partial \eta_C(W_K, W_P)}{\partial W_K} - $$
$$- \frac{f_E}{W_C(W_K, W_P)} \times \frac{\partial W_C(W_K, W_P)}{\partial W_K} > 0 \qquad (8)$$

(relation (8) is valid for the field of higher design performance)

$$\frac{\partial f_E(W_K, W_P)}{\partial W_P} - \frac{f_E}{\eta_{CE}(W_K, W_P)} \times \frac{\partial \eta_C(W_K, W_P)}{\partial W_P} - $$
$$- \frac{f_E}{W_C(W_K, W_P)} \times \frac{\partial W_C(W_K, W_P)}{\partial W_P} < 0 \qquad (9)$$

(relation (9) is valid for the field of lower design performance)

where

$$f_E = \frac{\partial M_{EE}}{\partial t} \times Q_E \times S_E(W_K, W_P) \quad \text{(kg/s)} \qquad (10)$$

f_E – the emission flow caused by energy transformation in the production process.

By a similar analysis we can find the relations specifying the behaviour of the function of specific emissions in view of the control parameter W_P, i.e. operating efficiency (Janeček, Mikleš 2003).

RESULTS

Basic mathematical analyses of the problem in question were carried out in the scope of our work with the objective to determine the optimum operating efficiency of logging and transport production systems with minimizing heterogeneous substances generated by the energy flow conversion during its transformation to the resulting product.

The constructed models were verified by the operation of a TERRI 20-40 forwarder (Figs. 2 to 4). Specifications of the conditions of work of the forwarder TERRI 20-40 and its technical parameters were presented in Janeček and Mikleš (2003).

The experiments have shown that the function of specific emission values always creates the minimum. The optimum operating efficiency ranges in dependence on the minimized emission constituents,

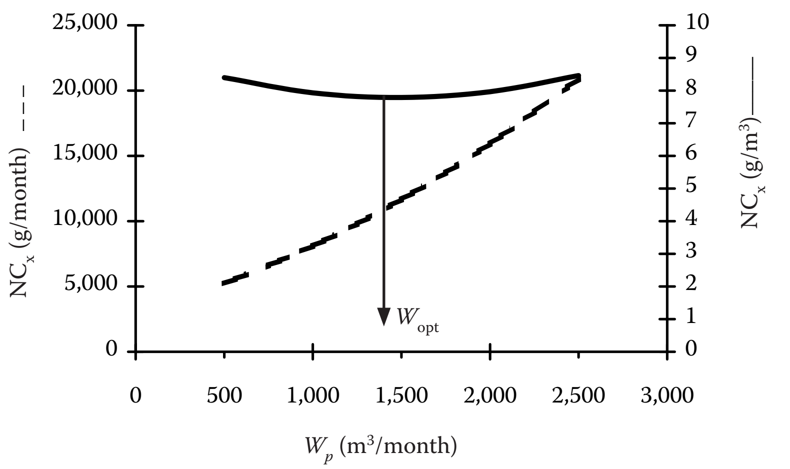

Fig. 2. Dependence of specific NC_x on operating efficiency – TERRI 20-40

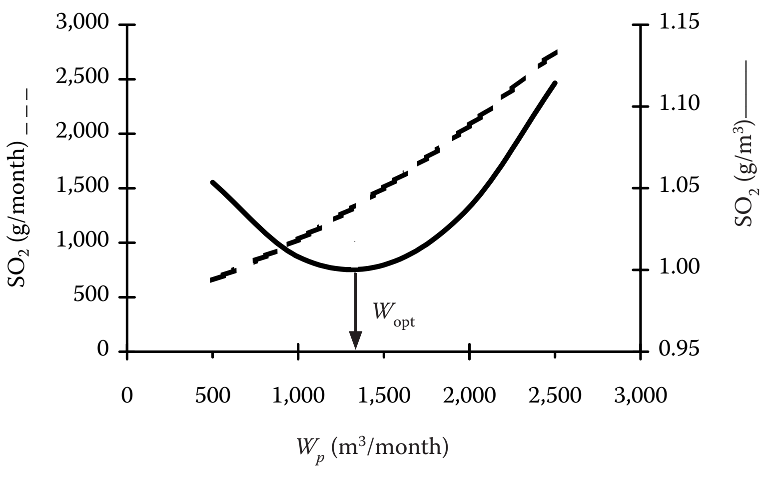

Fig. 3. Dependence of specific SO_2 on operating efficiency – TERRI 20-40

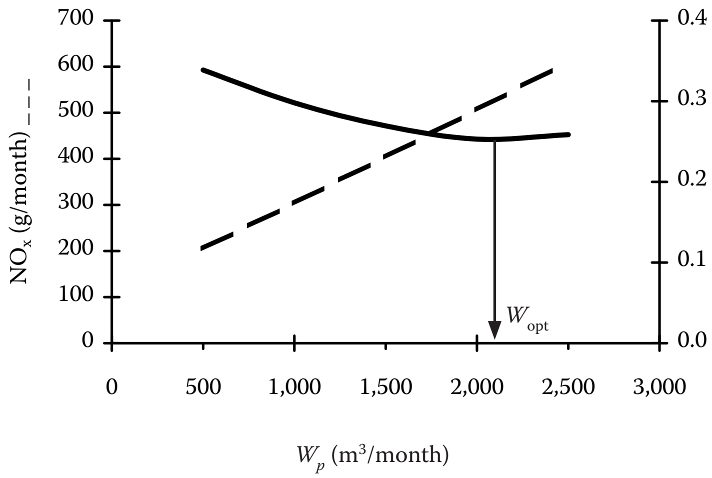

Fig. 4. Dependence of specific NO_x on operating efficiency – TERRI 20-40

namely: NC_x – 1,470 m^3/month, SO_2 – 1,310 m^3 per month and NO_x – 2,100 m^3/month. Selection of the optimum efficiency of the forwarder depends on the mathematical weight of emission constituents which can be determined by the significance of their impacts on the environment (Skoupý 2000). Ranges of produced emissions with the changing operating efficiency are shown in Table 1.

It follows from relations (8) and (9) that the design of the mobile off-road system affects both the flow of heterogeneous substance emissions, i.e. it affects the inherent emission, and the efficiency of energy transformation to the resulting product, i.e. it affects the efficiency of combustion. Similarly, the value of operating efficiency at which the mobile off-road system works affects the transformation efficiency and intensity of production of heterogeneous substances. The thesis (Duvigneaud 1980) that the quantity of dissipative energy is the measure of the environmental purity (emissions of heterogeneous substances) of work of the production system is valid in general. The thesis has been confirmed by the practical analysis of work of the mobile system mentioned above in dependence on the rate of its work.

Table 1. Sensitivity analysis of the dependence of heterogeneous substance emissions on the operating performance of TERRI 20-40 system

W_p (m^3/month)	NC_x	SO_2	NO_x
	minimum (g/m^3)		
	7.79	1.00	0.25
	deviation from minimum (%)		
1,300	0.19	0.02	11.97
1,310	0.16	0.00	11.74
1,390	0.00	0.07	9.90
1,400	0.01	0.08	9.69
1,500	0.05	0.31	7.67
1,600	0.07	0.69	5.93
1,700	0.36	1.24	4.46
1,800	0.82	1.94	3.27
1,900	1.44	2.81	2.35
2,000	2.32	3.85	1.70
2,100	3.17	5.04	0.00

DISCUSSION

The mathematical formulation of the production system behaviour (in logging and transport operations, but also valid for silvicultural operations) shown in this paper has confirmed that it can represent a basis for the determination of conditions the fulfilment of which leads to the optimization based on the determination of the minimum heterogeneous substance emissions related to the performance unit.

Thus, the solution provides an optimization of production system operations from the aspect of the minimum level of produced heterogeneous substances related to the production unit and the minimum costs related to the production unit, necessary for the transformation of production system into an environmentally cleaner method of production. The general thesis (Duvigneaud 1980) has been confirmed: by minimizing the dissipative energies produced by the production system, we can reach the operating mode of the production system characterized by the optimum work of the system with respect to environmental cleanness of the work.

Experimental measurements carried out on the TERRI 20-40 forwarder have revealed and substantiated that the upper limit of the operating efficiency recommended by the manufacturer (W_p ÷ 2,000 m^3 per month) is too high with respect to the emissions of heterogeneous substances.

It has been proved that the optimum operating efficiency of the TERRI 20-40 system ranges from 1,000 to 1,500 m^3/month.

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Racionalizace výkonnosti mobilního terénního systému pracujícího v lesním prostředí z hlediska jeho zátěže emisemi

ABSTRAKT: Článek se zabývá možnostmi minimalizace emise cizorodých látek (SO_2, NO_x a NC_x), vztahujících se na jednotku objemu zpracovaného dříví, a to na základě měření konstrukční a provozní výkonnosti mobilního terénního systému pracujícího v lesním prostředí. Lesní výrobní systém je zde chápán jako výrobní systém, do něhož vstupují materiálový a energetický tok a případně i tok pracovních sil. V době probíhajícího výrobního procesu je tok materiálu, energie nebo pracovní síly transformován na konečný produkt (zpracované dříví, příprava půdy, zalesňování atd.). Řídící veličinou optimalizující pracovní režim lesního výrobního systému je provozní, případně konstrukční výkonnost. Kriteriální funkcí specifikující optimalizaci parametrů mobilního terénního systému pracujícího v lesním hospodářství je množství emitovaných cizorodých látek, vztahujících se na jednotku práce vykonané výrobním systémem. Jsou stanoveny podmínky pro režim práce (výkonnosti) mobilního terénního systému pracujícího v lesním prostředí, za kterých je dosaženo minima emitovaných cizorodých látek, vztahujících se na jednotku vykonané práce. Teoretické závěry jsou experimentálně verifikovány.

Klíčová slova: lesnická technologie; SO_2, NO_x, NC_x; optimalizace; minimalizace

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