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Analysing all-terrain vehicles efficiency under conditions of snow-covered area

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Abstract. The paper studies the tasks of determining the efficiency of all-terrain vehicles under the conditions of snow-covered area. To assess the efficiency it is suggested to apply the ratio of the product of the transported cargo speed and maximum travel speed to the fuel consumption. The all-terrain vehicles were experimentally researched in December, January, February and March. The influence of chassis parameters on the machine efficiency was analysed. The study outcomes enable to assess the areas of all-terrain vehicles efficiency.

1. Introduction

Creating all-terrain vehicles for snow-covered areas is a sophisticated issue from the standpoint of maintaining an appropriate level of the transport high-traction. However, the high-traction criterion is not sufficient for assessing the performance of transportation and processing operations. Thus, calculation of the transport operation on snow is a key aspect in designing all-terrain vehicles. Generally, efficiency should be understood as the degree of compliance of machine characteristics with consumers requirements. Road transport is required to carry out transportation effectively, i.e. to transport cargo and passengers under the complicated road conditions, within the minimum period of time and with minimum operating expenditures. A very important research objective is to develop the chassis mechanical specifications providing efficient all-terrain vehicles manoeuvrability under the conditions of snow-covered area. This will enable to modify the existing all-terrain vehicles and to create the options with a high level of maneuverability.

The increase of the all-terrain vehicles efficiency under the conditions of moving on snow (ice road, large snow areas, access to the sites of mineral resources extraction) can be achieved by means of sophisticating the design of a machine itself as well as its running gear. Therefore, the development of the methods to select running gears mechanical specifications providing the efficiency of the all-terrain vehicles manuevering under the conditions of snow-covered area is a research problem of an utmost importance. The solution of the mentioned problem will enable to modify the existing all-terrain wheeled vehicles and to create the options with a high level of maneuverability.

Performance specifications require to apply different criteria to assess the efficiency of all-terrain vehicles performance characteristics. The objective of assessment is to compare different transports under similar operating conditions and to determine the most energy efficient one.

In work [1] the energy efficiency of an automobile was calculated on the basis of the ratio of the energy spent on cargo transportation to the energy of the required energy demands.

In his work Faskhiev H.A. [2] applies the efficiency coefficient determined by the ratio of an average operating velocity to the fuel consumption required for 100 km of the road with the purpose to assess fuel efficiency and tractive dynamic abilities of auto trucks.

Approach covered in [3] is based on defining the criterion of energy efficiency with regards to payload weight, fuel consumption per unit of the road, accelerations and speeds of an automobile, rotational inertia coefficient, streamlining factor incrementation as well as the fuel amount and properties.

Paper [4] is devoted to studying an efficiency coefficient of an automobile. The efficiency coefficient of the payload transportation is represented as the ratio of the vehicle average velosity, cargo weight, coefficient of running resistance to fuel consumption and its properties.

Paper [7] demonstrates the indicator of transport operating efficiency. The given indicator takes into account the cargo payload, transport route, fuel consumption and lower calorific value and density.

M.G. Becker suggested to assess wheeled vehicle manoeuvrability with the help of the efficiency coefficient [8] determined by payload, vehicle speed, fuel consumption per hour and rated cruising range.

J. Wong [9] suggested to apply tractive efficiency coefficient to characterise the efficiency of non-road vehicles with regards to implementing engine capacity in drawbar horse power. The tractive efficiency coefficient is determined by the ratio of drawbar horse power to the corresponding power produced by the engine. Transport efficiency determined as the ration of transport efficiency to the corresponding system input power is introduced in the paper.

Papers [10, 11] suggest the application of the following indicator equal to the ratio of the useful yield of hauling capacity on the wheels to the accomplished work of the rotational torque given to wheels with the purpose to assess energy efficiency of a wheeled vehicle during off the road operation. The author of paper [12] also uses a power-conversion factor to assess energy efficiency.

The decision about the essential usage of an indicator enabling to estimate the efficiency of all-terrain vehicles both on the basis of field evidence and calculations was taken in the scope of the given paper.

2. Efficiency accounting estimate

The outcomes of the performed analytical review state that nowadays there is lack of generally accepted indicators enabling to estimate the movement efficiency of wheeled vehicles under the conditions of snow-covered areas. The efficiency can be more completely characterised by comparing the operating results with the expenditures for obtaining this result.

The given paper suggests calculating the efficiency with regards to the following dependence:

$$E = \frac{mV}{Q} \quad (1)$$

where m is cargo weight, kg; V is velosity, km/h; Q is fuel consumption, l/100 km.

The mentioned efficiency indicator characterises the following: if in the situation of comparing two all-terrain vehicles with equal capabilities the fuel consumption for transportation activities of one all-terrain vehicle is smaller than the fule consumption of another one, than the efficiency of the first vehicle is considered to be higher. In case when two vehicles have common engine parameters it shows how high the efficiency of the most effective vehicle is.

Let us consider the calculating procedure with regards to the vehicles ZVM-39083 “Veya” 4x4 and ZVM-39083 “Veya” 6x6 (Fig. 1).

ZVM-39083 "Veya" 4x4

ZVM-39083 "Veya" 6x6

Figure 1. Subjects of research developed at LLC "All-terrain vehicles plant" (ZVM)

The subjects of research are represented by all-terrain vehicles ZVM-39083 "Veya" 4x4 and ZVM-39083 "Veya" 6x6. Their technical characteristics of the calculated and experimental analysis are given in Table 1. The snow and swamp-going vehicles under consideration are fitted with wheeled running gears on extra-low pressure tyres. Application of extra-low pressure tyres enables to reduce the pressure on a bearing surface. Chassis of the snow and swamp-going vehicle "Veya" 4x4 has an extended and strengthened frame, permanently-engaged 4WD with a lockable interaxle differential, portal axles with wheel reduction gear and an aluminum-alloy wheel, webs with balloon tire with the following size: 1300x700. The snow and swamp-going vehicle "Veya" 6x6 has a frame and a body which is larger than that of the vehicles with 4x4 axle arrangement, which is necessary for incorporating an additional driving axle. The transmission of this snow and swamp-going vehicle has a constant rear driveline and a concurrently linkable solid drive of the front and intermediate axles.

Table 1. Technical characteristics of snow and swamp-going vehicles under research

Technical characteristics	ZVM-39083 "Veya" 4x4	ZVM-39083 "Veya" 6x6
Gross weight / cargo-carrying capacity, kg	3300/700	3900/800
Length / width / height, mm	4900/2500/2750	5750/2500/2750
Engine type	Cummins ISF2.8	Cummins ISF2.8
Maximum capacity kW(h.p.)	88.3(120)	88.3(120)
Maximum rotational torque Nwm	270	270
Maximum velocity, km/h	50	50
Running gear	Extra-low pressure tyres	Extra-low pressure tyres

The formula used for calculating fuel consumption is as follows:

$$Q_s = g_e(P_c + P_w + P_a)/(36 * v * \rho_f * \eta_{tr}) \quad (2)$$

where g_e is efficient fuel-consumption rate g/(kWh), determined by the following formula: $g_e = g_{ep}K_eK_u$, where g_{ep} is fuel-consumption rate at engine power rating, K_e is a coefficient indicating engine rotational rate, K_u is a coefficient indicating engine capacity, determined by empiric formula for diesel engines: $K_u = 1.2 + 0.14U - 1.8U - 1.8U^2 - 1.46U^3$, where U is capacity, $U = (P_\psi + P_w)/P_\kappa$; ρ_f is fuel density, kg/l; η_{tr} is transmission efficiency factor; P_ψ is power, used for overcoming road resistance, kW; P_w is power, used for overcoming air resistance, kW; P_a is power, used for overcoming acceleration resistance; $K_e = 1.25 - 0.99E + 0.98E^2 - 0.24E^3$, where $E = n_e / n_p$ is the ratio of the current value of engine rotational frequency n_e to the rate of rotation at maximum capacity n_p.

When moving on snow the resisting power of a wheeled vehicle can be divided into 2 constituents:

$$F_c = F'_f + F_f \quad (3)$$

where F'_f is internal resistance power; F_f is external resistance power.

The internal resistance of a wheeled vehicle includes internal friction losses in the walls of tyres during their bending and unbending and internal friction losses in the tread tyres during their cyclic compression. The first term takes a larger part in resistance to the movement of a wheeled vehicle on snow. The external force of resistance to movement is composed of the following [13]:

$$F_f = F_{fc} + F_{rp} + F_{hp} + F_w \quad (4)$$

where F_{fc} is resistance to movement as a result of vertical snow strain by a running gear; F_{rp} is resisting power, generated by plunging a vehicle underbody into snow; F_{hp} is drawbar horse power; F_w is air resistance.

When calculating resistance to movement caused by vertical snow strain covered in paper [13], the following assumptions were admitted: snow surface is considered to be flat, a vehicle moves along the roadbed with a sufficient (but finite) snow depth, i.e. the influence of the underlying terrain microprofile is not considered and vehicle casing fluctuations are lacking, i.e. a quasistatic task is regarded.

The model of interaction of a single wheel with snow is suggested to be used for calculating resistance to movement within the framework of the mentioned assumptions. The interaction model structure is demonstrated in Figure 2.

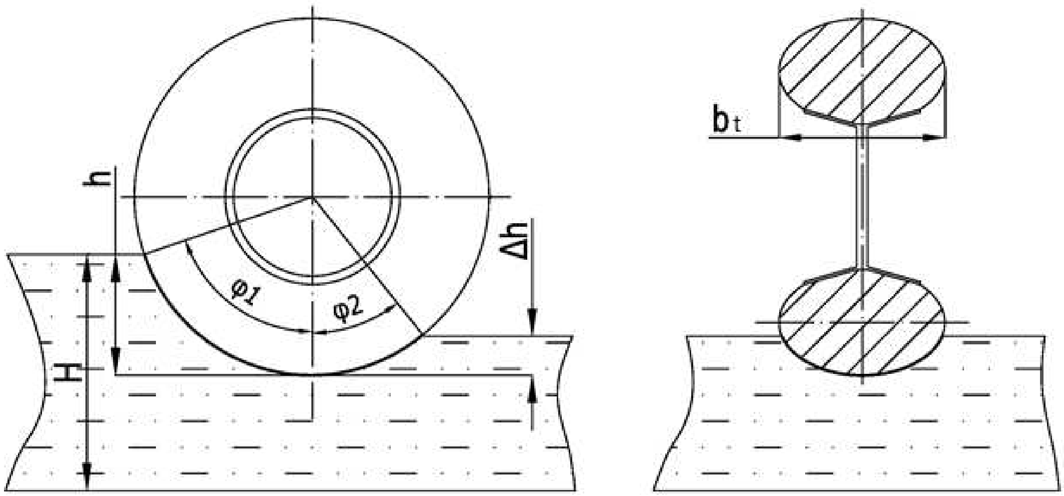

Figure 2. Model structure of a single wheel and snow interaction

The general concept of the model lies in iterational wheel plunging into snow up to the moment of achieving a balance (5) whereas respondence in snow grows at the growth of the depth of plunging.

$$R_k = G_k \quad (5)$$

Distribution of normal pressure in the area of wheel and snow contact is fixed at every stage. The given procedure is performed by dividing the area of wheel and snow contact into *n* of line elements in longitudinal cross section which is l_i long and normal cross section which is b_{ij} wide. Thus, the whole area of wheel and snow contact is represented by a set of n^2 of the elementary areas. Further, the normal pressure value q_{ij} is calculated at every segment. A distinguishing characteristic of the given model is the condition of tyre deflection when pressure ratings occuring in snow cover exceed the limit value of a tyre pressure. The tyre pressure comprises tyre air pressure and tyre carcass pressure; the given value is limiting for the beginning of a tyre deformation. Consequently, this addition enables to push the model closer to real conditions of wheel and snow contact. Reactions in snow occuring when plunging a wheel at the depth *h* are evaluated by calculating a surface integral (6)

$$R_k = \int_{\varphi 1}^{\varphi 2} d\varphi \int_{\theta 1}^{\theta 2} q_0 \cos^2(\varphi)\cos^2(atg(\cos(2\theta) - \frac{a^2 + (b\cos\varphi)^2}{(a^2 - (b\cos\varphi)^2)\sin(2\theta)}) - \theta)d\theta \quad (6)$$

Under the circumstances of the mentioned assumptions motion resistance force from the vertical snow strain includes the following components [14]:

F_{fc1} being a resisting power caused by the deformation of snow cover by a wheel is calculated according to the following dependence:

$$F_{fc1} = 2b\gamma h^2{}_{\max}\left(-\ln\frac{\gamma h_{\max}}{\gamma h_{\max} + q_{\max}} - \frac{q_{\max}}{\gamma h_{\max} + q_{\max}}\right) \quad (7)$$

F_{fc1} is a resisting power caused by the additional deformation of snow pressed out into wheel space [15]:

$$F_{fc2} = 2b\gamma h^2{}_{\max}\sum_{j=1}^{n}\left\{\ln\left[1 + \frac{\Delta h_j}{h_{\max}}\left(1 + \frac{q_{\max}}{\gamma h_{\max}}\right)\right] - \frac{\Delta h_j}{h_{\max}}\right\} \quad (8)$$

where b is a gauge width, m; γ is a coefficient of snow initial stiffness, kPa /m; $h_{\max}$ is a coefficient characterising the degree of snow deformation at the pressures corresponding to the maximum compression, m; Δh_j is depth of snow brought from the cotact zone into wheel space, as a result of excavating and bulldozer earthmover effects; $q_{\max}$ is maximum pressure in the contact between a wheel and a bearing surface, kPa.

Pulling power can be calculated by the equation [13]:

$$F = \frac{M_e U_{tr} \eta_{tr}}{r} \quad (9)$$

To determine the running gear spin, it is necessary to compare the value of this hauling capacity (from engine) with the hauling capacity of a wheeled running gear in touch with a roadbed.

For short-cut calculations the sufficient accuracy can be achieved by the following formula:

$$F_t = 0.8(c \cdot A + F_z \cdot tg\varphi)e^{-K_1 ls}(1 - e^{-K_2 ls}) \quad (10)$$

where *c* is a connectivity coefficient; $tg\varphi$ is a soil internal-friction coefficient; F_z is normal load; *A* is total contact area of a wheel with bearing surface; *s* is a coefficient of a wheeled running gear spin; *l* is a contact line length, K_1, K_2, are empirical coefficients.

Running speed can be calculated by this equation:

$$V = \frac{n_e r}{U_{tr}}(1 - S) \quad (11)$$

An experimental estimate of efficiency of the focused subjects of research was carried out in this paper with the aim to estimate the calculation method conformity. The fuel flow meter Corrsys-Datron DFL3x (Fig. 3) was used to measure fuel consumption. The fuel flow meter Corrsys-Datron DFL3x is the next generation of the renowned flow detectors of the firm Corrsys-Datron. Detectors of the DFL system are aimed at measuring fuel consumption in combustion engines.

Figure 3. Installation of DFL3x flowmeter in a carbody

The fuel economy and efficiency of transport were jointly estimated. Key points are installed on the section with the purpose to distinguish the segments with different characteristics of supporting base. Fuel metering is implemented in key points with the help of fuel flow meter DFL3x. Transport speed is determined with the help of Racelogic-VBOX.

Let us consider the program of transport testing. For testing, machine fuel tank is filled at least up to 75% with the GOST R 52368-2005. As appropriate, the machine can be fueled additionally. The vehicle starts moving, accelerates and continues to move at nominal engine speed. If there are tough roads to be passed, then engine capacity can be increased during the whole way.

Herewith, fuel consumption is fixed in liters. The speed of the vehicle under research is measured by means of the equipment for speed measurement in GPS coordinates. Fuel metering in liters is fixed at key points of the route. Fuel is metered 3-5 times. Mean values are used as fuel consumption calculated values. Fuel economy is determined as the ratio of the fuel consumption obtained as a result of the research to 100 km of distance run.

The comparison testing of the moving efficiency of the wheeled vehicles produced by LLC “ZVM” were carried out during winter months, namely December, January and February, as well as in March. The vehicles were fitted with the equipment for measuring speed characteristics and fuel consumption. It allowed to obtain data for eficiency calculation.

Measurements were executed in the middle of each month. Vehicles were tested on the company’s proof ground. The snow cover characteristics were measured before every testing with the help of the snow gage VS-43. Testing took place every 5-10 meters along the entire length of the route. The obtained data are demonstrated in Table 2.

Table 2. Measurement values of snow characteristics

Date	Snow depth, m	Root mean square deviation, m	Density, g/sm^3	Root mean square deviation, g/sm^3
15th December, 2018	0.32	0.041	0.18	0.029
21st January, 2018	0.49	0.028	0.22	0.033
17th February, 2018	0.55	0.03	0.25	0.035
10th March, 2018	0.42	0.05	0.20	0.03

Let us present calculated values of the efficiency under the conditions of moving on snow at the chosen dates (in December, January, February and March) for the obtained data. Figure 4 demonstrates the meter chart of efficiency for two wheeld vehicles ZVM-39083 “Veya” 4x4 and

ZVM-39083 "Veya" 6x6.

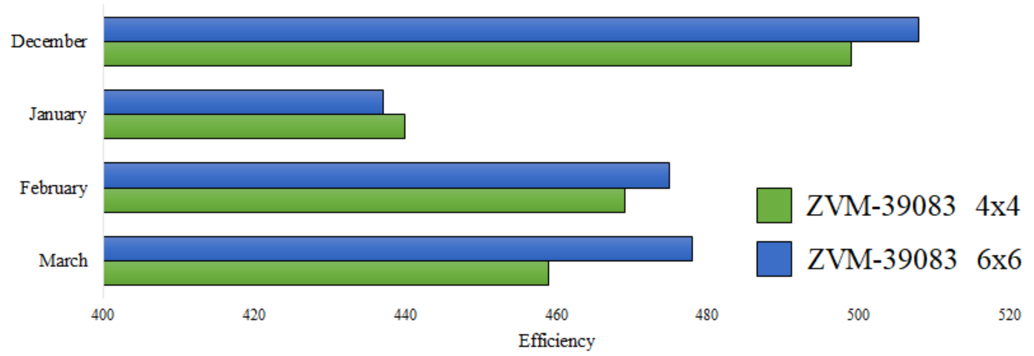

Figure 4. Meter chart of efficiency by month.

As we can see from Figure 3 efficiency values for the first vehicle are 8-11 units higher than for the second one. The experimental data presented in Tables 3 and 4 enabled to compare the obtained data with the theoretical data.

Table 3. Experimental data for ZVM-39083 "Veya" 4x4

	December	January	February	March
Fuel consumption, l/100 km	42.26	56.45	57.34	49.92
Average velocity, km/h	30.1	35.5	38.4	32.7
Efficiency	499	440	469	459
Deviation from calculated value	3.1%	0.8%	8.1%	0.5%

Table 4. Experimental data for ZVM-39083 "Veya" 6x6

	December	January	February	March
Fuel consumption, l/100 km	44.3	58.8	60.1	52.1
Average velocity, km/h	28.15	32.1	35.7	31.1
Efficiency	508	437	475	478
Deviation from calculated value	2.7%	14.1%	8.1%	5.3%

Thus, maximum deviation of efficiency from the calculated values is 14.1%. Consequently, the introduced method can be applied if the pattern of distribution of the main snow parameters is known. These data can be obtained using model [16]. The given model provides statistical data on the patterns of snow depth and density distribution during winter month.

When considering the issue of estimating vehicles efficiency (namely, moving on snow) during winter months, it is necessary to take into account the degree of its compliance with the conditions of the area where the vehicles will be exploited. If one of the tasks is providing effective vehicle movement on virgin snow, for example, for solvong transport and technological tasks in a separate area, then the choice of vehicles must be done on the basis of the weather conditions pattern during the year. Additionally, the choice of a vehicle must base on its applicability. For instance, if a machine cannot operate during a relatively small period of time while purchasing and exploitation of a machine with greater manoeuvrability will be considerably larger than the profit gained, then the first variant should be choisen [17].

Having snow statistical characteristics, namely, the density and depth during a year as well as the period and the starting dates of snow cover generation in different areas of the territory under consideration, it is possible to obtain all necessary parameters for estimating the efficiency of wheeled machines operation [17].

3. Conclusion

On the basis of information mentioned above, it is possible to conclude that the application of the described methods can help to obtain sound recommendations on how to select mechanical specifications of the running gears, which can favour the increase of efficiency of all-terrain vehicles movement on snow. The areas of the efficient utilization (technical and economic applicability) of several vehicles of various weight categories under the conditions of snow-covered areas can be defined as well.

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