ARPN Journal of Engineering and Applied Sciences

EVALUATION OF FUEL CONSUMPTION OF THE VEHICLE WHEN DRIVING ON SNOW

Aleksandr Blokhin, Lev Barakhtanov, Evgenii Fadeev, Elena Denisenko and Andrey Noskov
Nizhny Novgorod State Technical University named after R.Y. Alekseev (NNSTU), Nizhny Novgorod, Minin st., Russian Federation
E-Mail: a.n.blokhin@gmail.com

ABSTRACT

As an object of research we take the all-terrain vehicle on low pressure tires with a diesel engine. The purpose of the work is to determine the dependence of the vehicle's fuel consumption from basic design parameters of the engine, transmission, wheel and parameters of the snow. The paper describes a wheel-snow interaction model, describing the distribution of normal pressures, having the cosine law throughout the area of the tire contact, as well as records of changes in physical and mechanical properties of the snow during its deformation and destruction by the front wheels and repeated deformation by the rear wheels. We considered the structure of the resistance forces when moving on snow and determined the equity values of the main components. The most rational design parameters of the vehicle were obtained using methods of multivariate analysis. The paper shows the measuring equipment used forfield tests, including determining of the vehicle position and speed and the fuel consumption measuring. The paper provides the results of comparison between theoretical and experimental data. It has conclusions and recommendations how to reduce fuel consumption when driving on snow.

Keywords: snow properties, vehicle's fuel consumption, wheeled vehicle, low-pressure tire, rolling resistance on snow, tire-snow interaction model.

1. INTRODUCTION

Transport efficiency increase is the main problem in economy. Total energy consumption in transport sector of Russia (on railway, automobile, air, water transport and also gas and oil pipelines) grew in 2000-2010th by 50 % up to 200 million tonsinfuel equivalent that is 31.5% of all energy consumption (Expert online)

About 70 percent of energy source demand refers to automotive transport.

One of the directions of the transport efficiency increase is using special vehicles in severe conditions. The index, which is equal to the performance related to the fuel consumption, allows comparing such vehicles by their efficiency.

This article is dedicated to researching of factors having impact on the vehicles fuel consumption. These factors include both parameters of the vehicles and the properties of the supporting surface. Fuel consumption determines not only transport efficiency, but also successful transport work. There is no developed system of gas stations in the Northern area, that's why it is so important to know fuel consumption on certain route in order to predict the required fuel reserve.

Mathematical model

The possibility of driving on the snow road is determined by the presence of the snow traction, which represents the difference between the force applied to the wheel from the engine and motion resistance forces (Bekker, Wong).

The total resistance force, when driving on snow, is composed from resistance from: vertical deformation of the snow by the wheel (R_c), drawbar (R_{dr}), excavation-dozing effects (R_{doz}), crumpling of the snow by the vehicle bottom (R_{bot}), the air resistance (R_w), rolling resistance (R_f) and inertia forces during the relative rotation of the wheels (R_{in}) and is defined by the Eq. 1

$$R_{\sum} = R_f + R_c + R_{doz} + R_{bot} + R_{dr} + R_w + R_{in} \quad (1)$$

Originality of the snow properties greatly complicates the process of determining the values of the components of the resistance force, so not only theoretical but also experimental determination of the required parameters is needed.

The snow is a deformable supporting surface that is compacted and destroyed by driving. It is taken into account when calculating the motion resistance forces from compaction Eq.2 and from the excavation and bulldozing effect Eq.3 (Barakhtanov *et al* 1986, 1996, 2013). The calculations show that R_c and R_{doz} make a large part of the total resistance, therefore it is very important to calculate these values as accurately as possible.

$$R_c = 2b\gamma h_{max}^2 \left(-ln\left(\frac{\gamma h_{max}}{\gamma h_{max}+q_{max}}\right) - \frac{q_{max}}{\gamma h_{max}+q_{max}}\right) \quad (2)$$

$$R_{doz} = 2b\gamma h_{max}^2 \left[ln\left(1+\frac{\Delta h}{h_{max}}\left(1+\frac{q_{max}}{\gamma h_{max}}\right)\right) - \frac{\Delta h}{h_{max}}\right] \quad (3)$$

When

$$q_{max} = \frac{\gamma h_g h_{max}}{h_{max}-h_g} \quad (4)$$

$$h_{max} = H\frac{n_y b + d}{b + d}$$

$$R_{in} = \sum I_k \frac{\partial \omega_k}{\partial t} \quad (5)$$

Δh = snow depth exported from the contact zone to the cross-axle area as a result of excavation and bulldozing effects, [m]; H - snow depth, [cm];

h_{max} = snow deformation corresponding to the maximum compaction, [m];

q_{max} = maximum normal ground pressure under the vehicle's wheel, [kPa];
hg = wheel sinkage, [m];γ - coefficient of initial stiffness, [N/m3];
q_0 = normal ground pressure in central longitudinal section of wheel, [kPa];
b = width of wheel, [cm]; ρ_0 initial snow density, [g/cm^3];
I_k = wheel's mass moment of inertia, [Kg/m^2]; ω_k - wheel's rotation speed, [rad/s];

Actually, some of the above-mentioned components of total resistance are close to zero values. Since the wheels of the vehicle are big and the speed is low the R_{bot} and R_w are not taken into account, so R_{dr} is also assumed as equal to zero.

Maximum pressure greatly affects the stresses in the contact area of the mover with the supporting surface, which in turn determines the motion resistance force (Blokhin, *et al.* 2011). To calculate the resistance from compaction and from the excavation and bulldozing effects, the wheel sinkage model was developed (Barakhtanov, *et al.* 2015, Fadeev, *et al.* 2014). In this model some assumptions associated with the presentation of the tire were used: in longitudinal section it has the shape of a circle with a diameter D, and in the cross section the surface of the tire contact with the snow is in the shape of an ellipse (Figure-1).

The arc length L determines the values of the contact pressure of the tire on the ground according to the driving depth and the cosine law of distribution (Malygin)

$$q_0 = q_{max} \cos^2 \lambda \qquad (6)$$

The cross section of the tire in accordance with the assumptions of a sidewall was shown as an ellipse with axes a1 and a 2 (Figure-1)

Then, the pressure distribution in the cross section is taken as in Eq. 6.

$$q = q_0 \cos^2 \varepsilon \qquad (7)$$

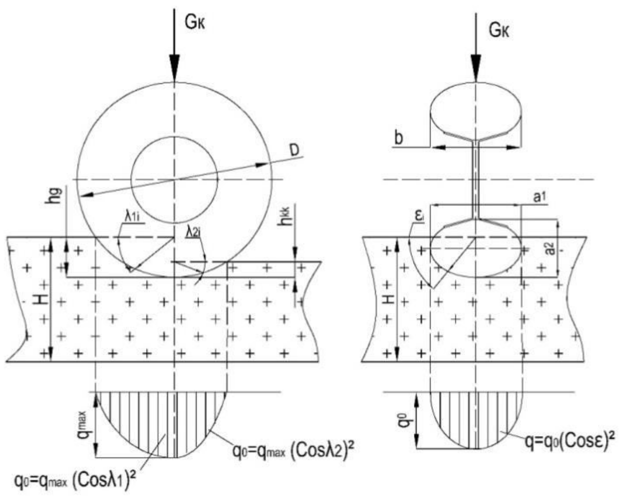

Figure-1. Scheme of the wheel sinkage model.

Thus, knowing the value of the pressure at each point of the longitudinal and cross sections of the tire we can obtain a picture of distribution of the normal pressure in the wheel contact patch with the snow, and considering the size of the contact patch, the resulting normal reaction. The wheel sinkage determines when the total reaction equals to the load per wheel. Furthermore, when the wheel passes over the snow its physical-mechanical properties change that must be considered when determining the forces acting in the subsequent interaction of the wheels with the snow. To calculate the new snow density and other main parameters after the wheel pass the regression dependencies were used (Barakhtanov *et al.* 2011, 2015). After that the resistance from compaction, from the excavation and bulldozing effects can be calculated.

The Figure-2 shows moving resistance from snow compaction when driving on snow, as a major part of the total resistance.

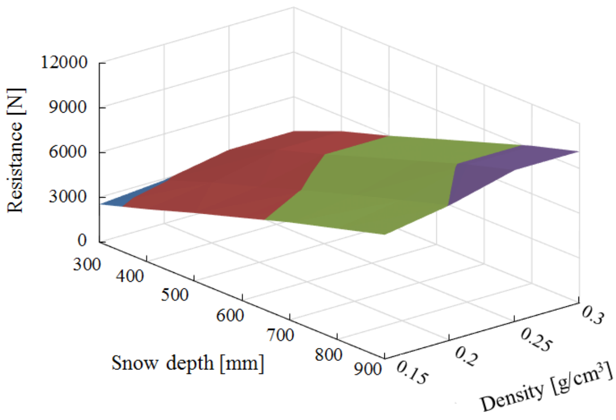

Figure-2. Dependency of the resistance from snow parameters.

Fuel consumption at steady motion is defined by well-known Eq. 8 (Kravec, Blokhin 2006):

$$Q_s = \frac{100 \cdot G_t(\omega_{ei}, \alpha_i)}{36 \cdot V \cdot \rho_t}, \qquad (8)$$

Where:
Qs - fuel consumption, [l/100 km]; Gt - fuel consumption per hour, [kg/h];
ω_{ei} - engine angular velocity , [rad/s]; a_i - engine load, [%];ρ_t - density of fuel, [g/cm3];
V - vehicle speed [m/s];

The fuel consumption per hour is determined in accordance with engine characteristic for a given engine. The engine load is defined from the full movement resistance (Equation 9), the vehicle's speed depends of the engine speed and the selected gear.

$$\alpha_i = \frac{N_l}{N_e} 100\% \qquad (9)$$

Where:

VOL. 11, NO. 21, NOVEMBER 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

$$N_l = \frac{\sum R r_0}{U_{tr}\eta_{tr}}$$

Where:

Ne = engine torque from engine gross performance characteristic, [Nm];
Nl = engine load torque from movement resistance, [Nm]; Utr - transmission ratio;
Uki = ratio of the gear number - i; ηtr - transmission efficiency;

Using the above mentioned equations the modeling of the terrain vehicle fuel consumption was made. Figures 3-5 show the curves of fuel consumption while driving on the snow having different densities.

The diagram on Figure-3 shows that while the snow depth grows, the fuel consumption increases progressively. For example, while moving at a speed of 10 km/h at the second gear on snow with ρ_0=0.15 the fuel consumption increases by 70% when H rises from 30 to 80. When ρ_0=0.2 and H rises from 30 to 70 the fuel consumption increases by 60%, etc.

Rising of the density at constant H leads to the increased consumption, because R_c rises too (Figure-2). For example, while moving at a speed of 10 km/h at the second gear, rising of the ρ_0 from 0.15 to 0.3 leads to increasing of the fuel consumption by 24% on the snow of H=30 and more than 45% on the snow of H=40.

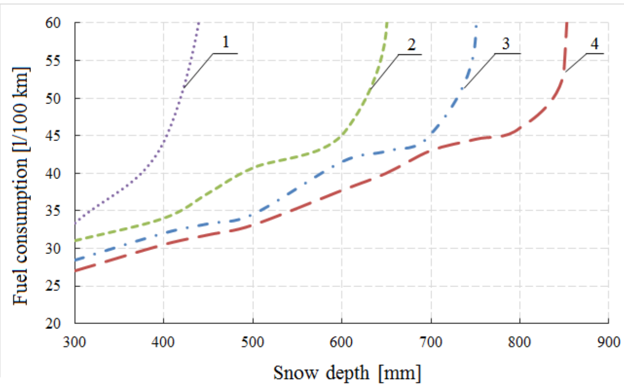

Figure-3. Dependency of the fuel consumption from the snow depth for different snow densities:
1 - 0.3 g/cm^3; 2 - 0.25 g/cm^3; 3 - 0.2 g/cm^3; 4 - 0.15 g/cm^3.
V =20 km/h;Slip = 25% Third and second gears.

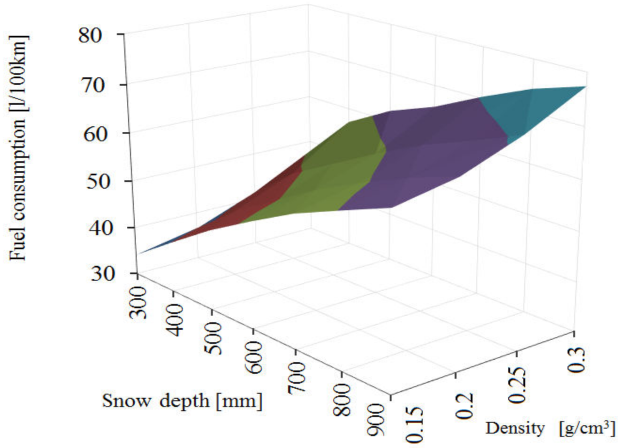

Figure-4. Dependency of the fuel consumption from the snow depth and density.
V =20 km/h;Slip = 25% First gear.

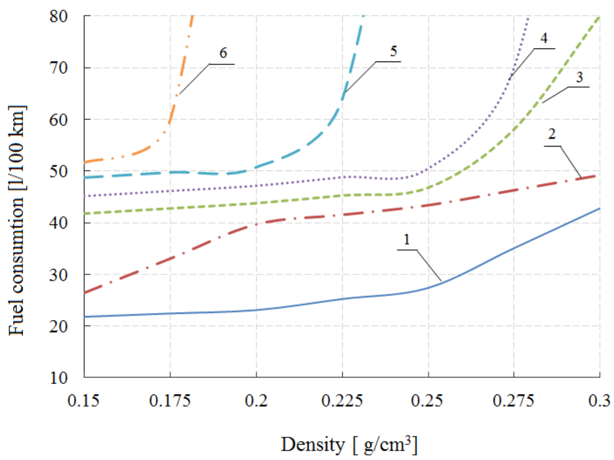

Figure-5. Dependency of the fuel consumption from the snow density, for different snow depths:
1- 300 mm(the thirdgear); 2-400 mm (the third gear –up to 0,15 g/cm^3, and the second gear from 0,2 g/cm^3); 3-500 mm (the second gear); 4-600 mm (the second gear); 5-700 mm (the second gear); 6- 800 mm (the second gear).V =20 km/h;Slip = 25%.

The regression dependencies of fuel consumption from snow parameters such as depth and density were obtained. For example, the data presented in Figure-5 can be expressed as Equation (10).

$$Q_S=-5.73+82.2\rho_0+95.4H+74.16\,\rho_0^2-31.1\rho_0 H-32.9*H^2 \quad (10)$$

Equation 10 shows that fuel consumption respectively grows when the snow density and/or the depth rises. This dependency is nonlinear, but it can be described by the equation of the second order withan insignificant error. Where in the consumption-density plane – it is an open up parabola, and in the consumption-depth it is an open down parabola (Figure-4).

Figure 5 shows the results of the terrain vehicle moving at the second and the third gears with a speed of

ARPN Journal of Engineering and Applied Sciences

20 km/h. While driving at the selected gear by shallow snow (H<60) and ρ_0=0.15-0.25 we can see the fuel consumption increase up to 12%. Curve 2 is an exception, it shows consumption at the snow depth H=40. Driving at the third gear is possible at ρ_0=0.15, and at higher density - only at the second gear.

The Eq. 11 shows the dependency of fuel consumption from the gearbox ratios on the snow with ρ_0=0.2 and H= 40.

$$Q_s = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 + \\ + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{14}x_1x_4 + b_{15}x_1x_5 + \\ + b_{23}x_2x_3 + b_{24}x_2x_4 + b_{25}x_2x_5 + b_{34}x_3x_4 + \\ + b_{35}x_3x_5 + b_{45}x_4x_5 \tag{11}$$

When x_1 - corresponds to U_{k1}; x_2 - U_{k2}; x_3 - U_{k3};x_4 - U_0; x_5 - U_{k5}.

Table-1. Regression coefficients for a fuel consumption equation.

Regression coefficient	Qs at 20 km/h, (l/100km)	Qs at 10 km/h, (l/100km)	Qs at 30 km/h, (l/100km)
b0	68.97	78.32	80.28
b1	0.00	0.00	0.85
b2	0.00	0.982	-3.379
b3	3.433	-2.280	1.718
b4	3.433	-0.743	-0.685
b12	0.00	0.00	0.4
b13	0.00	0.00	0.53
b14	0.00	0.00	0.014
b15	0.00	-0.775	0.631
b23	0.00	0.568	3.395
b24	-1.12	-1.305	0.329

The analysis of Equation (11) at speed 20 km/h shows, that the final and the third gears ratio affect the fuel consumption. The reduction of the mentioned ratios leads to decrease of the fuel consumption.

Analysis of Equation (11) at speed 10 km/h shows that the final, the third and the second gears' ratio affects the fuel consumption. The increase of the second gear ratio leads to the fuel consumption growth. The increase of the final and the third gears' ratio leads reduction of the fuel consumption. Meanwhile, the final and third gears' ratio has a greater impact on the consumption than the second gear ratio.

Analysis of Equation (11) at acceleration up to 30 km/h on snow with ρ_0=0.2 and H=40, shows that the reduction of the first and third gears' ratioand the increase of the second and the final gears' ratio leads to the reduction of the fuel consumption.

2. THE FIELD TESTS

In order to verify the obtained theoretical results we carried out experimental studies of the *RUSAK*all-terrain vehicle with the low-pressure tires, created jointly by the NNSTU employees and the *KOM* Group of Companies (Table-2, Figure-6).

Figure-6. Rusak test vehicle.

Table-2. Specification of the *Rusak* All-Terrain vehicle.

Axle configuration	4x4
Maximum speed, km / h	60
GVW, kg	3600
Carrying capacity, kg	800
Engine	Diesel Cummins ISF 2,8
Clearance, mm	450
Wheelbase, mm	2980
Speed on the water, min km/h	6
Angle of climb, min°	30
Passengers capacity	6
Front tires, rear tires	Extra-low pressure
Overall dimensions (LxWxH), mm	5400x2440x2810

During the field tests the fuel consumption at various constant speeds was determined; measurements were carried out like (Blokhin *et al*., 2015). The studies were carried out using high-precision equipment, including theVBox 3i multifunctional speedometer (the *Racelogic* Company) and the VZP-4 flow-meters (Aquametro Company).

Figure-8 shows the results of theoretical calculations and experimentally measured values of thefuel consumption when driving of a vehicle with Gross vehicle weight = 3400 on the snow with: ρ_0=0,227, γ=44,973, tgφ=0, 3543 and H=40. From the data it follows that the discrepancy between the theoretical and the experimental values is about 15% on the average.

VOL. 11, NO. 21, NOVEMBER 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

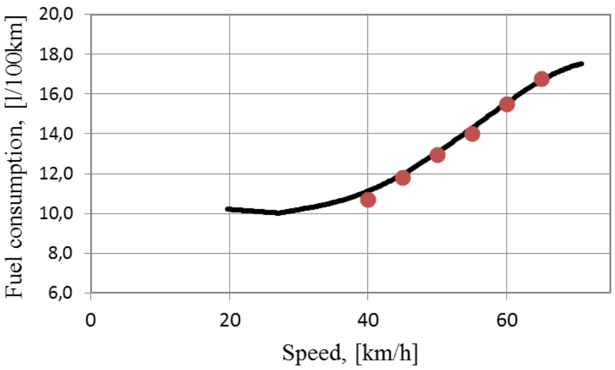

Figure-7. Comparison of the experimental and the calculated data obtained when driving at the fifth gear. Points - test data; line - calculated data.

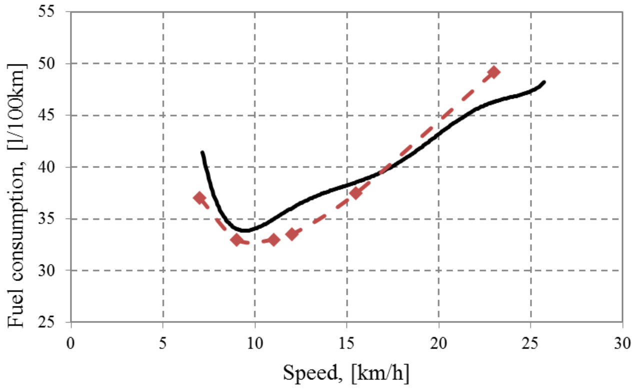

Figure-8. Comparison of the experimental and the calculated data obtained when driving on snow at the second gear (ρ_0 =0.25, H=.40) Points - test data; line - calculated data.

3. CONCLUSIONS

Expressions for determining the vehicle fuel consumption when driving on snow, as well as fuel consumption, depending on the basic design parameters of the vehicle and the physical and mechanical properties of snow and the snow depth obtained using multivariate analysis methods were provided.

The paper presents the characteristics of the measuring equipment used during the experimental studies, including settings for the measurement of physical and mechanical properties of snow (stiffness, density, coherence, angle of internal friction, etc.), the distribution of pressure in the wheel contact with the snow, measurement of traction forces, measurement of kinematic parameters of the vehicle movement and measurement of fuel consumption.

Rising of the density at the constant snow depth leads to increased consumption, because the moving resistance from the snow compaction rises too. Similarly with the increase of the snow depth with a density in the range 0.15 ... 0.3 g/cm^{3}the fuel consumption increases progressively. The fuel consumption respectively grows when the snow density and/or depth rises. This dependency is nonlinear, but it can be described by the equation of the second order with an insignificant error. Where in the consumption-density plane - it is an open up parabola, and in the consumption-depth it is an open down parabola

The research of the dependencies of fuel consumption from transmission ratios when moving on snow with ρ_0=0.2 and H=40 shows that:

- at the speed of 20 km/hthe final and the third gear ratios affect the fuel consumption. The reduction of the mentioned ratios leads to the decrease of the fuel consumption.

- at the speed of 10 km/hfinal the third and the second gear ratios affect the fuel consumption. The increase of the second gear ratio leads to the fuel consumption growth. The increase of the final and the third gear ratios lead to the reduction of the fuel consumption. Meanwhile, the final and the third gear ratios have a greater impact on consumption than the second gear ratio.

- at the acceleration up to 30 km/h, the reduction of the first and the third gear ratios and the increase of the second and the final gear ratios lead to the reduction of the fuel consumption.

The analysis of the results of the experimental and theoretical studies shows a good convergence. The discrepancy between the data does not exceed 15%

ACKNOWLEDGEMENTS

This work was carried out at the NNSTU named after R.E. Alekseev, with financial support from the government in the face of the Russian Ministry of Education under the Federal Program "Research and development on priority directions of the scientific-technological complex of Russia for 2014-2020", the unique identifier of the project: RFMEFI57714X0080.

REFERENCES

[1] Anikin AA, Barakhtanov L.V., Donato I.O. 2009. Trafficability of tracked vehicles on snow, Omega, Nizhniy.

[2] Barakhtanov L.V., Ershov V.I., Kuljashov A. P., Rukavishnikov S.V. 1986. Over-snow vehicles, The Volga-Vyatka publishing house, Gorky.

[3] Barakhtanov L.V., Belyakov V.V., Kravec V.N. 1996. Trafficability of automobile. Nizhniy Novgorod State Technical University, Nizhniy Novgorod.

[4] Barahtanov L. V., Blokhin A. N., Denisenko E. G.,2011. Research of mechanical-and-physical properties of snow for a trafficability of vehicle. Topical questions of machine science. 1, 222-227.

[5] Barakhtanov L.V., Belyakov V.V., Blokhin A.N., Denisenko E.G. 2012. Mathematical dependence of physical-mechanical properties of snow cover as

support base for movement of vehicles. SCIENCE and EDUCATION: electronic publishing. 8, 85-104.

[6] Barakhtanov L.V., Blokhin A.N., Denisenko E.G., Noskov A.M. 2013. Method of determining of resistance force on snow of wheeled vehicles. Topical questions of machine science. (2): 179-185.

[7] Barakhtanov L.V., Blokhin A.N., Denisenko E.G., Fadeev E.A. 2014. Assessment of design parameters wheeled vehicles at its performance travelling on snow. Topical questions of machine science. (3): 128-131.

[8] Barakhtanov L.V., Blokhin A.N., Denisenko E.G., Fadeev E.A. 2015. Evaluation of vehicle performance on snow. Proceedings of the 13th Eur. Conf. of ISTVS. pp. 335-349.

[9] Bekker M.G. 1960. Off-the-road locomotion, The University of Michigan Press, Ann Arbor.

[10] Blokhin A. N. 2006 Development of the method for rational transmission ratios determination taking into account vehicle's operational properties and its functions. Ph.D. thesis. Nizhniy Novgorod.

[11] Blokhin A.N., Zezyulin D.V., Gorelov V.A., Belyakov V.V. 2011. Researches of interaction of the pneumatic wheel with ultralow pressure and the snow roadbed. SCIENCE and EDUCATION: electronic publishing. 8, 1-10.

[12] Expert online, 2012. Mozhet no ne hochet. http://www.expert.ru/northwest/2012/15/mozhet-no-ne-hochet/ (accessed 15.02.2016).

[13] Fadeev E.A., Blokhin A.N., Barakhtanov L.V. 2014. Modeling of the wheels sinkage to the snow surface. Topical questions of machine science. Issue 3, 147-150.

[14] Kravec, V.N. 2007. Theory of automobile. Nizhniy Novgorod State Technical University, Nizhniy Novgorod.

[15] Malygin, V.A. 1971. Investigation of snow deformation under track and rational choice for oversnow vehicles track dimensions, Doctoral thesis. Gorky.

[16] Wong J.Y. 1989. Terramechanics and off-road vehicles. Amsterdam (The Netherlands): Elsevier Science Publishers B.V.