640. Investigation of movement of the off-road vehicles under roadless conditions

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Abstract. The popularity of hybrid power trains has been increasing in off-road vehicles in the recent years. These vehicles operate under difficult road conditions. The aim of the reported work is to define the influence of hybrid power train during movement under difficult conditions.

Keywords: hybrid power trains dynamics, off-road vehicles, difficult road conditions.

Introduction

Increasing application of hybrid power trains is currently observed, particularly in the case of passenger cars. With energy saving and environmental pollution problems becoming increasingly important the usage of hybrid power trains is continuously expanding including also the off-road vehicles.

Scientific publications are already available that consider hybrid power trains in military transporters, so called Extra High Mobility Vehicles (EHMV), designed for movement under extremely difficult conditions. Hybrid power trains are promising in reducing environmental pollution and more efficient use of internal combustion engine (ICE). However, taking into account larger mass and cost of the power train, the optimal solution will require the analysis of energy consumption. This is particularly important when a vehicle is expected to be used in different conditions and it may be required to move along roads of varying quality including off-road conditions in the case of, for example, rescue and recreational vehicles.

During evaluation of movement of the wheeled vehicles the road pavements are divided into two categories: a) the non-deformed pavements when the road deformation resulting from the machine weight is small and the model “rigid way - deformed wheel” can be applied; b) deformed pavements (soil), when the model “deformed road - deformed wheel” has to be implemented. In the case of movement along the road with relatively non-deformed pavement the energy consumption is evaluated using forces or energy balance equations (1):

$$\sum F_{\tau i} = \sum F_{ai} \tag{1}$$

where: $\sum F_{\tau i}$ - traction forces, $\sum F_{ai}$ - resistance forces.

Traction force $\sum F_{\tau i}$ is obtained by summing traction forces exerted by wheels of separate axles. Rolling resistance force $\sum F_{ai}$ is obtained by summing resistance forces [1,2]:

$$\sum F_{ai} = ma\delta + mg\left(i + f\right) \text{ if } v \le 15 \text{ m/s} \tag{2}$$

$$\sum F_{ai} = ma\delta + mg\left(i + f + k_v v^2\right) \text{ if } v > 15 \text{ m/s} \tag{3}$$

where: m - vehicle mass, a - vehicle acceleration, δ - coefficient accounting for rotation inertia of transmission, g - free fall acceleration, I - tangent of angle of uphill (slope), f - rolling resistance coefficient.

In the case of movement along the road with deformed pavement it is necessary to take into account additional factors – additional losses, required to deform ground and the fact that the vehicle mostly moves at the limits - when the resistance and adherence rates are close resulting in the wheel slip that reaches 20 - 40 % [2,3].

A model of movement of EHMV-type vehicle along the roads with deformed pavement is investigated in the current research work. Proposed algorithms are based on conventional principles of traction control systems – when the slip exceeds the optimal slip ratio, the torque for the next cycle period is reduced and vice versa. The study aims to determine how successful the system is by modeling the movement under difficult conditions - very high rates of resistance to movement and a relatively large wheel slip reaching 30 - 50 %. Since straight movement under difficult conditions is unlikely, the new algorithm evaluates that the rear wheels of 30 % of the width will form a new track that is why the drag coefficient was increased by evaluating the difference between the front wheels forming a new track and the rear wheels moving by track already formed.

Characteristics of the research object

The results of earlier investigations [4,5], which were used in the Gorki automobile factory for civil versions developed, are applied for the further research. GAZ 33058 “SADKO” and GAZ 33325 “EGER” arrangement were designed on the basis of GAZ 66. An advantage of GAZ-66 is its higher mobility (we could develop controllable rear axle) and adjustable tire pressure system. The double cab variant was investigated. Aggregates of hybrid power train are located similarly to those in the work [5]. Data of vehicle and engines are presented in Table 1.

Table 1. Vehicle data

Vehicle	*Mass*, kg		R_{z1}, N	R_{z2}, N	*a*, mm	*b*, mm
	load	full				
Double cab Hybrid	0	4038	21087	18526	1543	1757
	1720	5758	22445	34041	1989	1311

R_{z1}, R_{z2} – load of front and rear axis; *a* and *b* – distance of the center of the gravity to front and rear axles respectively.

ICE Engines

No.	Type	Displacement, l	Number of cylinders	Power N_{max}, kW/ rpm	Torque M_{max}, Nm/rpm
1	Diesel	3	L-4	122/3500	380/1250
2	Diesel	4	L-4	183/3450	570/1270
3	Diesel	4	L-4	62/2380	250/1400
4	Gasoline	4.2	V-8	88/320	285/2250

Electromotor (EM)

Rated / max inverter DC input voltage	Rated power (1Hr)	Max torque	Max rpm
650V/900V	67 kW	430 Nm	10000

The model of a vehicle moving along the deformed ground

Movement resistance coefficient was estimated using the mixed procedure from the work [6] – by assessment of the typical pavement characteristics and ground deformation process with the moving driving wheel and experimental material from the testing of the off-road vehicles on dirt-roads [7,8]. To simplify the theoretical models the drag coefficient for the front axle was determined when depth of rut was estimated:

$$h = \sqrt[3]{\frac{R_z^2}{k^2 w^2 D}} \tag{4}$$

where: R_z - vertical loading, k - coefficient of volumetric deformation of ground, w - tire width, D - tire diameter.

When h is known, resistance force $F_{ai} = R_x$ can be determined for ground types being examined [1,2] and obtained:

$$f_x = R_x / R_z \tag{5}$$

f(h) dependences are presented in Fig. 1 and are approximated by the equation:

$$f_x(h) = a_0 + a_1 h + a_2 h^2 \tag{6}$$

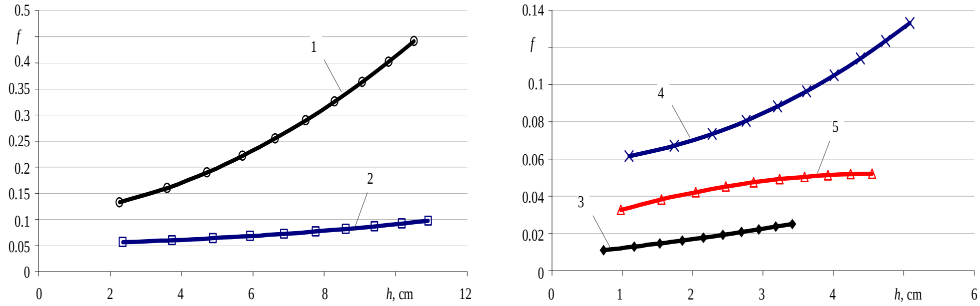


Fig. 1. Dependence of resistance force coefficient f on the rut depth: 1 – plough, 2– sand, 3 – clay, 4 – sandy loam, 5 – loam

Traction force is determined according to the methodology provided in [1,2,6-7]. It is evaluated taking into account possibility of ground displacement when wheel is working. φ_x is defined by friction between the tire and the ground and cutting forces, required to cut off prism edges at sides of the ground covered with off-road tires [2]. Depending on the soil properties wheel slid is estimated:

$$\chi = sign\left(\dot{\varphi}_r r_d - v\right)\left(1 - \left(\frac{\dot{\varphi}_r r_d}{v}\right)^n\right), \text{ where } n = \begin{cases} +1 & if \quad f\,\dot{\varphi}_r r_d > v \\ -1 & if \quad f\,\dot{\varphi}_r r_d < v \end{cases} \tag{7}$$

When components of factor f_x are defined traction force $R_x = F_\tau(\chi, R_z)$ and adhesion factor is then estimated:

$$\varphi(\chi) = \frac{F_\tau(\chi, R_z)}{R_z} \tag{8}$$

Dependencies of two types were obtained (Fig. 2):

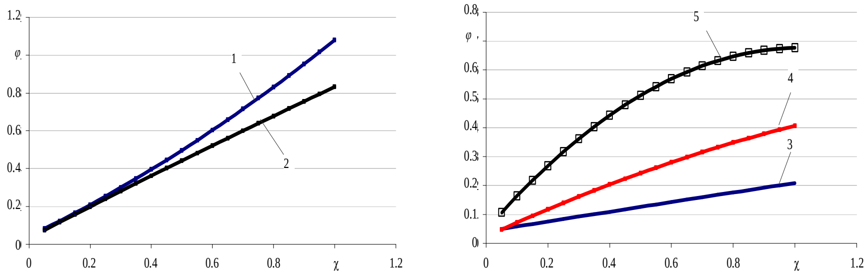


Fig. 2. Dependence of grip coefficient on the sliding coefficient: 1 – plough, 2 – loam, 3 – sand, 4 – sandy loam, 5 – clay

Dependence of type 1 is approximated by the equation:

$$\varphi(\chi) = b_0 + b_1 \chi + b_2 \chi^2 \tag{9}$$

And dependence of type 2 is approximated by the equation:

$$\varphi(\chi) = \frac{k_1 \chi}{(k_2 + \chi)^2} \tag{10}$$

Coefficients for the wheels of the second axle are determined by analogy with an assessment of lower deformation of soil according to the experimental data published in [7]. Thus tables of coefficients for typical soils are prepared.

When adhesion and resistance coefficients were determined the algorithm was developed that allows simulation of driving under difficult conditions on different pavements (Fig. 3). It consists of these blocks – block of state of vehicle batteries, EM, ICE, vehicle dynamics and road data blocks. The algorithm suggests a short-term use of EM - when there is not enough power of the ICE and when the car is stopped under non-extreme conditions.

ICE and EM operational modes are set using methodology proposed in [10]. By analogy method, the engine torque and instantaneous energy consumption with partial loading were determined.

The algorithms presented here are adapted to driving habits of control of a skilled driver. The system delay time is selected according to driver's reaction – 0.1 s for the transition modes (acceleration or deceleration, the gear shifting period) and 0.4 -1.0 s for the steady mode.

Simulation results

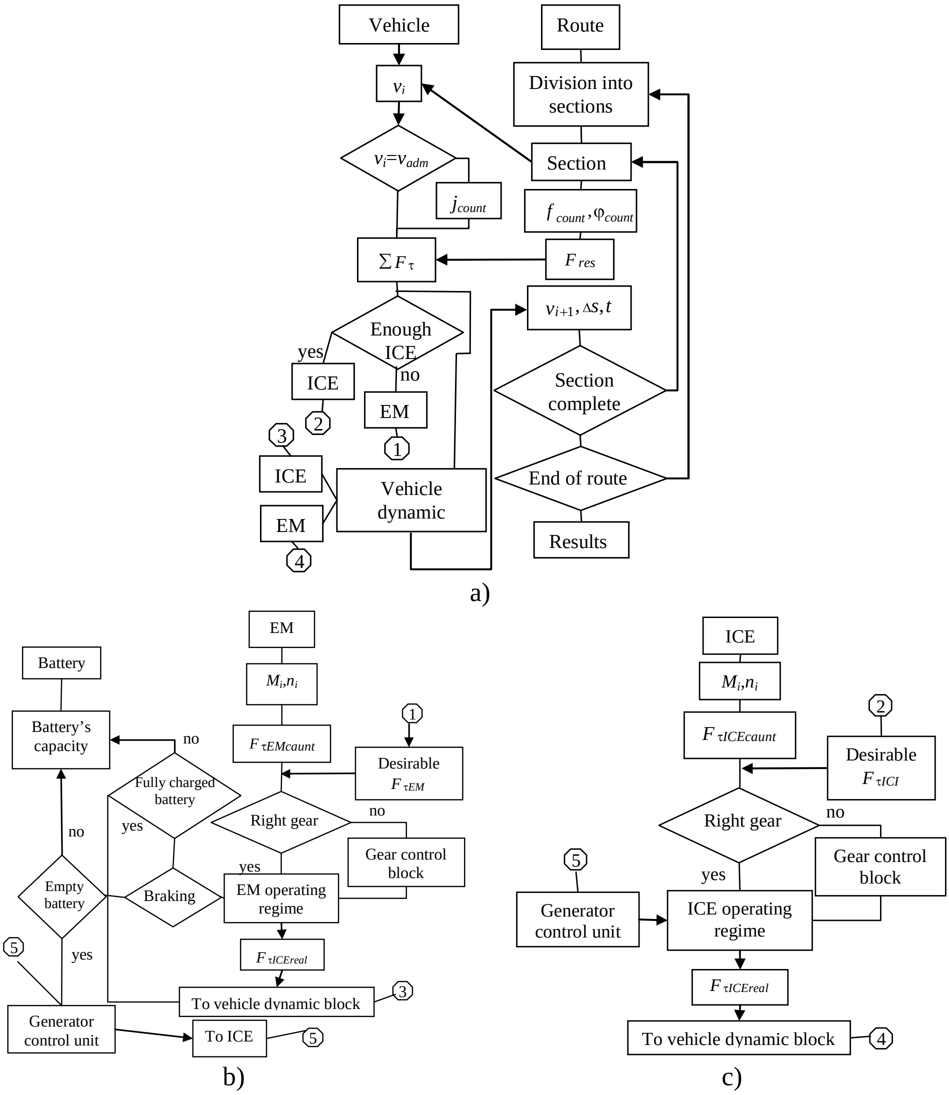
To check the model the stretch of road of 4182 m length with different road pavements was developed. This stretch consist of 5 different types of soil (Fig. 1, 2), uphill and downhill (slope 7^0).

The simulation demonstrated that the proposed algorithm represents movement conditions in the soils with sufficient accuracy – results of the simulation correlate with the experimental data provided in [6-8]. Modeling of the influence of engine power revealed that, despite the fact that at low rates of adhesion and differences of slip factors, full exploitation of engine power failed and engines with power reserve run in more rational modes.

Another feature of the results – low-speed motors designed for agricultural machinery in difficult conditions are more effective (engine No. 3) (Fig. 4). In terms of energy consumption a gasoline engine (No. 4), as the standard motor of the off-road GAZ 66, is irrational. Since most of the time ICE runs in the transitional mode hybrid power train proved to be effective and capable of reducing energy costs.

Modeling of EHMV dynamics enabled comparison of the estimated moments in wheels (given by the algorithm presented in Fig. 3) and the moments realized with the evaluation of the engine performance and traction. Slip conditions and algorithms of engine operating at optimum condition in some cases do not allow movement at the maximum permissible speed for the road conditions. This is particularly evident for the engine No. 3 – the engine performance does not allow realization of the desired acceleration. Initial results of the simulation have demonstrated that negative values of traction moments, when there is a possibility of using braking energy for recuperation, are quite rare (Fig. 5). Therefore, the possibilities of energy recuperation in difficult driving conditions are low and it is necessary to provide additional generator or opportunity to the electric to work in generator mode from ICE with a car driving under lighter conditions and with some ICE power. This opportunity is entered into the algorithm (Fig. 3, b).

Dynamic loadings of different aggregates were investigated by means of the model described in [11,12]. It allows simulation of vehicles for transmission. The model does not introduce major changes: it is provided that the inter-axial differential is not used in a distribution box, so the wheels of front and rear axles turn at equal speeds and their slide is the same. Modeling provided results on dynamic loads in transition modes of the main units - the clutch, the gear box, the distribution box and the axle shaft. Variation of moments acting in time is presented in Fig. 6. It was determined that a large tire slip leads to the increase of the transmission vibrations with respect to driving on the road with a hard pavement (Fig. 6). Hybrid power train can reduce the load in ICE transmission part, however, it should be provided lighter EV control by regulating variation rate of the torque.



a)

b)

c)

Fig. 3. Algorithm of movement under difficult conditions: a) vehicle dynamics and road data blocks; b) block of batteries and EM; c) block of ICE

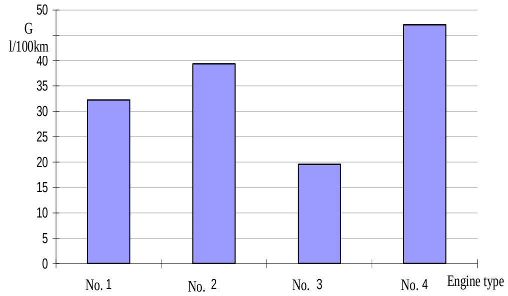
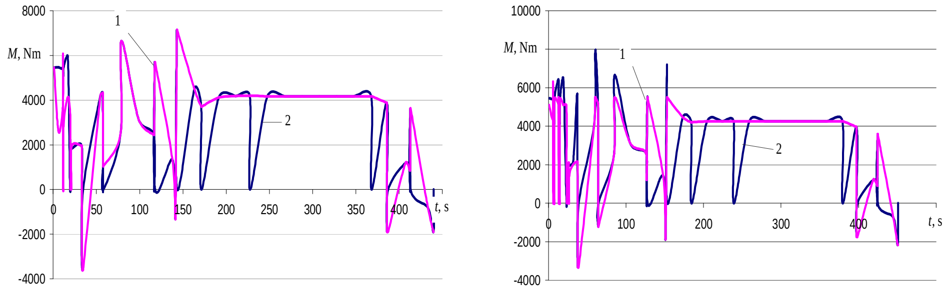
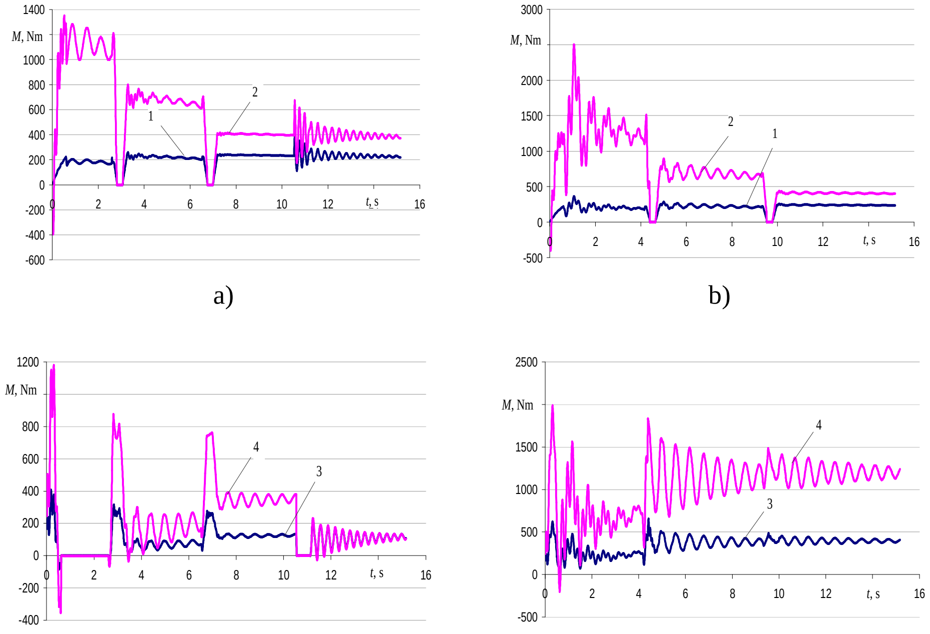


Fig. 4. Fuel costs EHMV with different power aggregates



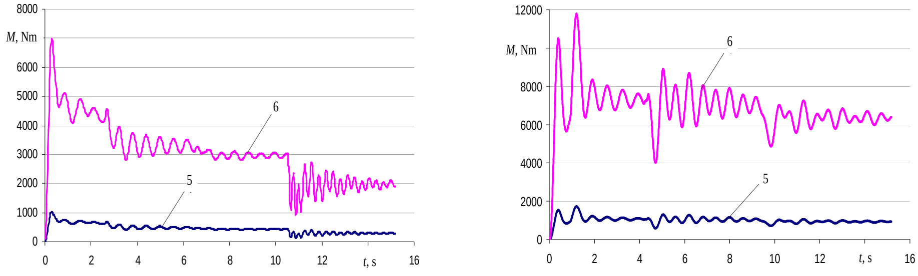
a) b)

Fig. 5. Values of traction moment given (1) and the realized one (2) with ICE No. 3 (a) and ICE No. 2 (b)



a) b)

c) d)



e) f)

Fig. 6. Moments, acting in different aggregates of transmission: 1- in ICE clutch, 2 - in ICE junction of gear box - distribution box; 3 - in EM clutch; 4 - in EM junction of gear box - distribution box; 5 - in cardan shaft from distribution box to rear axle shaft, 6 - in rear axle shaft. a,c,e - moving on asphalt; b,d,f - moving on deformed ground. ICE No. 3 + EM

Dependence analysis suggests that even in the case of movement under difficult conditions it is possible to exploit the advantages of the hybrid power trains, particularly, if stops are planned. In this case with the use of EM it is possible to avoid losses in ICE clutch and try to regenerate energy during braking. Analysis confirms that for this type of vehicles it is difficult to predict the energy consumption. Therefore it is necessary to run the generator with controllable gear that may charge the battery when required.

Conclusions

A model of the off-road vehicles moving in roadless conditions was developed that allows the optimal choice of engines of hybrid power plants and provides the possibility to assess driving under more realistic conditions.

Specific features of adjustment of automatic traction control systems were defined in the case of movement under challenging road conditions.

Possibilities of reduction of transmission loadings in transition modes were determined.

The advantages of hybrid power trains were confirmed by energy economy when driving through the off-road terrain.

The performed analysis indicates that the potential energy recuperation on slopes is questionable.

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