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Functional Adaptation of the Grain Carrier with Unstable Weight of the Transported Grain

Abstract: The methodology of functional adaptation of a grain truck by adjusting the speed depending on the density of the transported grain crop is proposed. As a result of studying the functional adaptation of a grain truck with an unstable mass of transported grain, it was found that fluctuations in the grain cargo during transportation significantly affect the stability of the vehicle, especially during maneuvering and braking. When estimating the weight of a grain truck, the density of the transported grain must be taken into account. The volumetric carrying capacity of a grain truck is carefully assessed by establishing a functional dependence on such parameters as nominal carrying capacity, volumetric carrying capacity, body volume, and cargo volume. The dynamic space of grain truck operation is based on a metric state space, each element of which fully determines the state of the system under consideration according to certain functional parameters. If one or more functional parameters of the grain truck are unstable and deviate from their nominal values, the grain truck may lose its functional stability and not perform the functions defined by the regulatory and technical documentation. In such cases, the dynamic operating space is characterised by transfer functions that provide a mathematical basis for analysing the behaviour of the system. During the operation of a grain truck, the task of ensuring its functioning in one of two areas is solved: the area of operation or the area of optimal operation. To ensure that the grain carrier operates in the optimal region, it is necessary to select such nominal values of functional parameters and tolerance fields to ensure the position of the spread and outputs in this region.

Keywords: functional adaptation, grain carrier, grain mass, mass instability, acceleration, equation of motion.

Introduction

Ukraine is rightly considered a grain country due to the efficient transportation of grain from fields to granaries, from elevators to processing plants, and to seaports. Ukraine has created a KrAZ "Karavan–2" grain haulage train consisting of a KrAZ-6511 C4 dump truck and a

PCWi-33 dump trailer with technical and economic indicators on par with foreign analogs (*Stehantseva, 2013*).

The KrAZ-6511C4 grain truck is equipped with a 400-hp Weichai Power WP12. 400E40 (Euro 4) with SCR exhaust gas cleaning system, MFZ 430 clutch and Fast Gear 12jS180TA manual transmission. The chassis is equipped with a reinforced rear axle balancer suspension, a front axle with an increased payload of up to 8 tonnes, and an integral steering mechanism. The payload of the vehicle is 20 tonnes and the trailer is 24 tonnes.

The results of factory and operational tests confirm the effectiveness of the KrAZ "Karavan–2" grain truck in agricultural enterprises (*Stehantseva, 2013*).

The applied theory and practice of road train, all-wheel drive vehicle and off-road vehicles are described in several works (*Panchenko et al., 2021*; *Burennikov et al., 2013*; *Zanko et. al., 2019*), on the basis of which the rational values of energy efficiency and parameters of KrAZ grain carriers during grain transportation are substantiated in two works (*Dun & Pavlenko, 2015*; *Dun & Klapan, 2013*). However, these works do not reflect the results of studies on the functional stability of an all-wheel drive truck with instability of the transported cargo weight. In the joint work of S. Dun and V. Klapan (*Dun & Klapan, 2013*), the economic efficiency of using the KrAZ "Karavan–2" grain truck train for transporting grain over a distance of 400–500 km was determined and it was found that its use for short distances (up to 50 km) is impractical.

The performance of road trains is determined by their average speed and carrying capacity. The possibilities for increasing the average speed of road trains are limited (*Barabash & Kravchenko, 2002*), so the most promising way to increase productivity is to adjust the speed depending on the density of the grain crop (wheat, barley, oats, etc.), i.e., the volumetric carrying capacity (t/m^3).

Functionally, vehicle stabilisation is assessed by its dynamic properties, manifested in the vehicle's response to control influences (*Podrygalo & Sheludchenko, 2015*). This paper proposes using the value of the acceleration (linear or angular) of a car that occurs when creating a controlling influence as a criterion for controllability. It is proposed to use this criterion to evaluate the dynamic properties of a car not only when turning, but also during acceleration and braking, i.e., controllability is characterized by the accuracy of changing the movement parameters according to the driver's desire. Thus, handling is the ability of a vehicle to respond adequately to driving influences. This manifests the dynamic properties of cars while driving, taking into account the applied forces.

The study aims to develop a methodology for the functional adaptation of a grain carrier by adjusting the speed depending on the density of the transported grain crop.

To achieve this goal, it is necessary to solve the following tasks:

- substantiate the functional model of a grain truck;
- develop a methodology for determining the functional stability of a grain carrier when the weight of the transported grain changes;
- develop practical recommendations for ensuring the functional adaptation of a grain carrier.

Results

Mathematical Modeling of Grain Truck Movement

When a grain truck is moving steadily uphill with an angle *a* (*Figure 1*), the following forces act on it

- gravity G_a, applied at the centre of mass C_a of the vehicle, which can be decomposed into the components G_a *sina* and G_a *cosa*;
- the air resistance P_w, the point of application of which is at the height of the centre of sail, taken equal to the height h_c;
- reaction P_h applied to the mechanism of coupling of the vehicle with the trailer at the height h_k (it is assumed that P_h is parallel to the bearing surface);
- normal reactions R_1 and R_2, shifted by a value $(n+m)$ from the projection of the wheel axles.

Having compiled the equations of moments of all applied forces relative to the points of applied normal reactions and bearing in mind that the sum of

$$(R_1 + R_2)\frac{n+m}{r_k} = G_a f\, cos\alpha ,$$

we obtain the following relations for normal reactions:

$$\begin{aligned} R_1 &= G_a \frac{b}{L} cos\alpha - P_w \frac{h_c}{L} - G_a f \frac{r_k}{L} cos\alpha - G_a \frac{h_c}{L} sin\alpha - P_h \frac{h_k}{L}, \\ R_2 &= G_a \frac{b}{L} cos\alpha + P_w \frac{h_c}{L} + G_a f \frac{r_k}{L} cos\alpha + G_a \frac{h_c}{L} sin\alpha + P_h \frac{h_k}{L}. \end{aligned} \tag{1}$$

Neglecting the air resistance (P_w=0) and assuming that the driving wheels of the car are the rear wheels, its traction properties are estimated only by the R_2 reaction. Replacing the reaction P_h of the trailer link in equation (1) with its value:

$$P_h = (l_{fv} - 1) G_a (f\, cos\alpha + sin\alpha) = (l_{fv} - 1) P_a ,$$

Where

P_a is the traction force on the driving wheels of the vehicle in the absence of the trailing link,

l_{fv} is the vehicle load factor.

In addition, since.

$$P_a \frac{h_c}{L} = (G_a\, sin\,\alpha + G_a f\, cos\,\alpha) \frac{h_c}{L} ,$$

then

$$G_a \frac{h_c}{L} sin\,\alpha = P_a \frac{h_c}{L} - G_a f \frac{h_c}{L} cos\,\alpha .$$

In this case, transforming equation (1), we obtain

$$R_2 = G_a \frac{a}{L} cos\alpha + P_a \frac{\left[h_c (l_{ft} - 1) h_k\right]}{L} - G_a f \frac{h_c - r_k}{L} cos\alpha . \tag{2}$$

where

l_{ft} is the trailer load factor.

The expression in square brackets in (2) is the reduced height of the centre of gravity of the grain truck, which is greater the higher the load factor and the height of the hitch. For h_k=h_c and the value of the load factor l_{ft} =D_v: D_t=2, where D_v and D_t are the dynamic factors of the vehicle and trailer, respectively. The traction force of the grain truck with the rear drive wheels at the road adhesion coefficient φ is equal to P_c=$R_2\varphi$. For this case, the dynamic factor of the grain truck in terms of traction is written as

$$D_c = \frac{a\varphi \cos\alpha}{l_{ft} L_p - \varphi\left[h_h + \left(l_{ft} - 1\right)h_k\right]}. \tag{3}$$

Since the last term of equation (2) is negligible (no more than 0.5 % of R_2), the rolling resistance coefficient f is not included in (3).

The variable forces acting on the grain truck are related either to the displacements or to the velocities of the points of application of these forces. The functional relationship that links the magnitude of the force and the kinematic parameters is the characteristic of the force. The force modulus in this relationship can also be a function of the arguments. For ease of calculation, we will assume that the force modulus is a function of the kinetic parameters for given characteristics.

The equations of motion are used to determine the laws of motion of mechanical systems under given forces (*Syvak & Derevenko, 2014*). The number of these equations for grain carriers with holonomic links is equal to the number of degrees of freedom of the grain carrier. The equations of motion of a grain carrier can be represented in various forms based on the theorem of change of kinematic energy. In the integral form, the equation of motion of a grain truck has the form:

$$\sum_{i=1}^{n} T_i - \sum_{i=1}^{n} T_{i0} = \sum_{i=1}^{m} A_k , \tag{4}$$

where

T_{i0}, T_i are the kinetic energy of the link and the grain truck, respectively, at the beginning and end of the time interval under consideration,

A_k is the work of each of the external and internal forces acting on the grain truck during a given time interval,

n is the number of moving links,

m is the number of forces.

Equation (4) is quite cumbersome even for simple traction units, since it is necessary to summarise the forces. For a grain carrier with one degree of freedom, a simpler form of this equation can be obtained, in which all summation operations are performed in advance. For this purpose, equation (4) is replaced by the equation of motion of a single point of the grain truck, which moves so that its generalised coordinate coincides at any time with the generalised coordinate of the grain truck. The dynamic model of a grain truck will be a material point with mass m_p moving under the action of a force F_n so that the generalised coordinate S of this point coincides with the generalised coordinate of the grain truck at any given time.

It is always possible to determine such values of F_n and m_n that the equation of motion of the actuator point is identical to the equation of motion of the grain truck and, therefore, the generalised coordinate of the actuator point will coincide with the generalised coordinate of the grain truck at any time. In this case, the equation of motion of the fulcrum is written in the form of an energy integral for some finite time interval during which the generalised coordinate changes from S_0 to S, and the reduced mass (for the grain truck, this value is variable) changes from m_n to m_{n0}:

$$\frac{m_n v^2}{2} - \frac{m_{n0} v_0^2}{2} = \int_{S_0}^{S} F_n dS \,, \tag{5}$$

where

v is the velocity modulus of the point of reference,

v_0 is the value of v at $S=S_0$.

To ensure the identity of equations (4) and (5), it is necessary and sufficient to fulfil the conditions:

$$\int_{S_0}^{S} F_n dS = \sum_{k=1}^{m} A_k \,; \tag{6}$$

$$\frac{m_a v^2}{2} = \sum_{i=1}^{n} T_i \,. \tag{7}$$

When the condition in dependence (4) is fulfilled, the condition is also satisfied for any moment of time:

$$\frac{m_{n0} v_0^2}{2} = \sum_{i=1}^{n} T_{i0} \,. \tag{8}$$

The reduced force F_n can be found from (6), and the reduced mass m_n can be found from (4). Thus, the reduced force is a force conditionally applied to the point of reduction and is determined from the equality of the elementary work of this force to the elementary work of forces and pairs of forces acting on the links of the grain truck (car, trailer). The equality of elementary work simultaneously means the equality of powers of the elements of the grain truck:

$$F_n v = \sum_{i=1}^{m} N_k \,, \tag{9}$$

where

F_k is the power of the force (pairs of forces) acting on the grain truck link.

Given the velocity v_k of the point of application of the force F_k acting on the grain truck link, ω_k of the angular velocity of the grain truck link acted upon by a pair of forces with moment M_k, the reduced force F_n is calculated by the formula:

$$F_n = \sum_{k=1}^{m} \left[F_k \frac{v_k}{v} cos\left(F_k, v_k\right) + M_k \frac{\omega_k}{v} \right]. \tag{10}$$

This sum can be both positive and negative, i.e., the reduced force is a scalar value. The minus sign indicates that the force F_n is directed in the opposite direction to the velocity v of the point of actuation. The reduced force F_n can be considered as a scalar magnitude that coincides with the generalised Lagrange force, which is determined by the ratio of the sum of the possible work of forces applied to the links of the grain truck. From dependence (7) it follows that the reduced mass of the grain truck can be defined as the mass that the point of actuation must have in order for the kinetic energy of this point to be equal to the kinetic energy of the grain truck's links. The kinetic energy of the link

$$T_i = \frac{m_i v_{si}^2}{2} + \frac{J_{si} \omega_i^2}{2} \,, \tag{11}$$

where
m_i is the mass of the link,
v_{si} is the modulus of the velocity of the centre of mass of the link,
$\omega_i F_i$ is the modulus of the angular velocity of the link,
J_{si} is the moment of inertia of the link relative to the axis passing through the centre of mass perpendicular to the plane of motion.

Considering (11), transforming (7), we obtain the following dependence for estimating the mass of the link

$$m_n = \sum_{i=1}^{n}\left[m_i\left(\frac{v_{si}}{v}\right)^2 + J_{si}\left(\frac{\omega_i}{v}\right)^2\right]. \tag{12}$$

n general, to build a dynamic model of a grain truck, any point on the grain truck can be chosen as the point of reference, i.e., the point where the mass is concentrated. Therefore, the reduced mass of a grain truck can be defined as the mass that must be concentrated at the point of actuation so that the kinetic energy of this point is equal to the kinetic energy of the truck and the grain truck trailer.

The reduced force and reduced mass do not depend on the speed of the point of impact, as the formulas for determining them include only the velocity ratios. For example, if the speed modulus of the point of origin v changes by a factor of k, then v_k, v_{si} and ω_i change by the same factor, while their ratios to v remain unchanged. It follows that the determination of the reduced forces and masses can be performed without knowing the velocity of the point of reference, i.e., before solving the equation of motion. This is the main advantage of reduced forces and masses. This conclusion can also be reached by paying attention to the fact that formulas (7) and (8), in addition to the given constants, include only analogues of velocities that do not depend on time. Let the reduced force F_n be given as a function of the generalised coordinate S (displacement of the point of reference). The reduced mass m_n is a function of the coordinate S. In this case, to determine the law of motion of the actuator, it is convenient to apply the equation of motion in the form of an energy integral with initial conditions t=0, $S = S_0^{v=v0}$. The velocity of the point of reference as a function of the generalised coordinate S is written as

$$v = v_p = \sqrt{\frac{2}{m_n}\int_{S_0}^{S} F_n dS + \frac{m_{n0}}{m_n}v_0^2}\ , \tag{13}$$

where v_p is the operating speed of the grain truck.

In some cases, the integral in the root expression of formula (13) can be represented in the final form. Then, after integration, we will obtain the function $v=v(S)$ either in the form of a graph or in the form of a series of eigenvalues for changes in displacement S from S_0 to some value that determines the end of the movement stage under consideration.

When estimating the mass of a grain truck according to dependence (12), it is necessary to take into account the density of the transported grain, which can vary within 300–820 kg/m^3 depending on the moisture content of the grain, temperature and pressure of the medium, as well as the type of grain transported (*Table 1*).

The relationship between the mass and volume of grain is defined by the formula $V=m/Q$, where V is the volume, m is the mass (carrying capacity), and Q is the bulk density of grain.

The dependence of the volumetric carrying capacity of the KrAZ-6511C4 grain truck is estimated by the following parameters:

Q_n is nominal payload of 15.4 tonnes;

Q_{lc} is volumetric payload of 1.3 m^3;

V_b is body volume of 11.81 m^3;

V_c is cargo volume of 20.53 m^3.

The fuel efficiency of KrAZ grain carriers significantly depends on the volume of transported grain, which was determined during factory tests and by operating organisations using different methods (*Table 2*) (*Dun & Pavlenko, 2015*).

The test methodology is based on the public road network available near the PJSC «AvtoKrAZ» vehicle manufacturing centre, taking into account the location of road facilities, structures, traffic conditions and terrain. The length of the circular route is 37 km, with sections of traffic in highway and urban conditions, with ascents, descents, bridges, railway crossings, etc. The road surface on the route is asphalt concrete. It is noted that with the increase in the length of the route, the decrease in the density of transported grain crops, fuel consumption decreases (*Table 2*).

Functional Stability of the Grain Carrier

A grain carrier belongs to the class of complex technical systems, the efficiency of which is ensured over a given period of time when performing its general functions within the limits established by regulatory requirements, provided that external destabilising factors are counteracted.

In general, a grain carrier (*Figure 2*) is represented as a system with control function vectors $U(t)$ and disturbance vectors $F(t)$ as input. The output variables characterising the functional parameters of the grain truck are represented by the vector-function $Y(t)$. The dynamic properties of the grain carrier are characterised by the transfer function $W_t = S_o / S_m$, where S_o and S_m are the output and control parameters, respectively.

The grain truck is influenced by both controlled input vectors—control functions ℓ_i ($i(t)$ is transmission gear ratio, $q(t)$ is fuel supply, $k(t)$ is steering gear ratio, $p(t)$ is brake control force) and uncontrolled m_i ($R(t)$ is driving resistance, $C(t)$ is road terrain, $B(t)$ is wind loads, etc). The output variables $Y(t)$ are characterised by the driving speed $v(t)$, the stability of the direction of movement $y_d(t)$ and braking $y_b(t)$, and the stability of the dynamic properties $w(t)$ of the grain truck.

Typically, disturbances $F(t)$ are determined by the instability of the output (functional) parameters $v(t)$, $y_d(t)$, $y_b(t)$, and $w(t)$. When comparing these parameters with their values v^x, y_d^x, y_b^x and w^x, at which the grain carrier operates stably, the controlled input variables $u(t)$ are adjusted at the comparison links ξ_v, ξ_d, ξ_b and ξ_w.

The functional parameter $v(t)$ is characterised mainly by the input control functions $i(t)$ and $q(t)$ and determines the operational properties of the grain truck, the parameters $y_d(t)$ and $y_b(t)$ are determined mainly by $v(t)$, disturbances in the direction of movement $f_d(t)$ and braking $f_b(t)$ and are aimed at ensuring the safety of the grain truck. The dynamic parameter $w(t)$ characterises the movement of a grain truck in the longitudinal, horizontal and vertical planes under the influence of forces in these planes.

The dynamic space of grain truck operation is based on the metric state space, each element of which fully determines the state of the system under consideration by the functional parameters $v(t)$, $y_d(t)$, $y_b(t)$ and $w(t)$. In case of instability of one or more functional parameters of the grain carrier $v(t)$, $y_d(t)$, $y_b(t)$ and $w(t)$, characterised by deviation from the nominal values of y^x, y_d^x, y_b^x and w^x, it is possible that the grain carrier will lose its functional stability, in which case it will not perform the functions defined by the regulatory and technical documentation (R&D). In this case, the dynamic space of grain carrier operation is determined by the transfer functions W_v, W_{yd}, W_{yb} i W_w, characterised by the relationship $v(t)$, $y_d(t)$, $y_b(t)$, $w(t)$ to y^x, y_d^x, y_b^x, w^x.

During the operation of a grain truck, the task of ensuring its functioning in one of two areas is solved:

OA is the area of operation in which the grain carrier operates according to its intended purpose (the required traction force, stability of the direction of movement and braking, etc. are ensured);

AF is the area of optimal operation, for example, according to the energy saving criterion, in which the grain carrier operates at an acceptable change in speed (change in acceleration within acceptable limits) (*Figure 3*).

AF of the grain

In this figure, the points B_y and B_g indicate, respectively, the operation of a grain truck in an unsteady mode of operation without acceleration and the permissible area for energy saving; Δ_v is the margin of optimal operation; V_o, V_f are the vectors of optimal and actual operation, respectively; ΔB is the margin of operation in the AF region.

Each point of the AF characterises a certain mode of operation of a grain truck at a certain point in time and is described by a certain combination of values of functional parameters, disturbing influences, and the initial state (*Figure 2*). The deviation of the point B_g from the point B_y (*Figure 3*) reflects the margin of optimal functioning Δ_v of the grain truck

$$\Delta B_z = \frac{z_{jk} - z_{jn}}{z_{jn}} = \frac{\Delta z_j}{\Delta z_{jn}}; \ \Delta B_x = \frac{x_{ik} - x_{in}}{x_{in}} = \frac{\Delta x_i}{\Delta x_{in}}, \tag{14}$$

where

z_{jk}, z_{jn}, x_{ik}, x_{in} are the critical values of the studied and boundary parameters along the x, z coordinates,

Δx_j, Δx_i is the margin of optimal functioning of the grain truck at the value of $\Delta z_{jn}$and Δz_{in}.

The margin of optimal functioning Δ_v is the deviation of the functioning vector V_f, whose components are the actual values of the functional parameters, from the nominal vector V_o, i.e. $V_f = V_o + \Delta_v$. In this case, to ensure the operation of a grain carrier in the optimal area of the OA according to Figure 3, it is necessary to ensure the selection of such nominal values of the functional parameters and tolerance fields for them that ensure the position of the spread and outputs in this region.

Given the known requirements for the optimal functioning of the grain carrier in the area of OA, which is determined by the parameters: nominal z_{np}, current z and permissible z_{rp} ($z_{np} < z_{rp}$), the density of distribution of the parameter value, taking into account its spread $f^{o}(x)$ and deviation $f'(x)$, should be determined:

- the probability that the parameter value will not go beyond the specified tolerances ($x_{np}<x<x_{vp}$) during a certain time of grain truck operation, taking into account disturbing influences;
- the tolerance limit ($x_{np}<x<x_{vp}$) and the corresponding requirements for the grain carrier not to exceed the probability of the parameter exceeding the tolerance of the specified permissible probability;
- planes $f(x)$ and $f'(x)$, under which the conditions that the probability of going beyond the tolerance will be less than the permissible probability will be fulfilled.

To solve this problem, all the functional parameters of the grain carrier are classified by parameters with specified nominal values X_O^C (Figure 3—$y_1(t)$, $y_2(t)$, ..., $y_n(t)$) and into parameters whose optimal value must be determined X_O^V (Figure 3—the OO region). They are written in vector form:

$$X_O^C = \begin{bmatrix} X_{oi}^{c} \\ \dots \\ X_{oj}^{c} \\ \dots \\ X_{oN}^{c} \end{bmatrix}; \ X_O^V = \begin{bmatrix} X_{oi}^{v} \\ \dots \\ X_{oj}^{v} \\ \dots \\ X_{oM}^{v} \end{bmatrix} \tag{15}$$

so that any functional parameter of the grain truck is a component of the vectors X_O^C and X_O^V.

Predicting the probability of a grain truck being in the optimal region of functioning of the OA (according to *Figure 3*) at time t is determined by the equations of the Markov process:

$$P_i = \text{v}_\text{i} P_i(t) + v_{i-1} P_{i-1}(t) \tag{16}$$

under nominal conditions i = 0, 1, 2, 3; t_o = 0; $P_i(t)$ = P_i.

When assessing the functional stability of a grain truck by only one parameter, for example, by the speed of movement $v(t)$ (*Figure 3*), its functioning can be evaluated by the function $\vec{x}_V = (v_i,\dots v_n)$. The vector $\vec{x}_V$ corresponds to the number $R(\vec{x})$, where $R(\vec{x}) > 0$ and increases to ∞ at $\vec{x}_V \to \vec{v} = (v_i,\dots v_n)$, where $\vec{v}$ is the critical vector. $R(\vec{x}_V) \to \infty$ and at $v_i \to \vec{V}_i = (V_i,\dots,v_n)$. In this case $R(\vec{x}) = [N_i(\vec{x}_V)]^{\pm 1} / [z(\vec{x}_V)]^2$, where i=1.2; a>0 is an arbitrary number; $z(\vec{x}_V) = \prod_{i=1}^{n} |v_i - V_i|^{q_i}$; $N_i(\vec{x}_V) = \sum_{i=1}^{n} \alpha_i |v_i - V_i|$ and a_i >0 is the weighting factor of v_i; q_i >0 is an arbitrary number.

When q=1/(n–1), q>a>1, we can write

$$R(\vec{x}_V) = \sum_{i=1}^{n} \alpha_i |v_i - V_i| \sqrt{\prod_{i=1}^{n} (v_i - V)}. \tag{17}$$

In this case, the functional stability of the grain carrier in terms of the parameter $v(t)$ is estimated using the following dependence

$$H(\vec{x}_V)=1/R(\vec{x}_V). \tag{18}$$

This function describes the functioning of the grain truck provided that v_i reaches the value V_i when changing $H(\vec{x}_V)$ within the range from H_{max} to 0 (when $v_i=V_i$), characterising the functional stability of the grain truck in terms of speed $v(t)$.

Similarly, the functional stability of the grain truck can be assessed by the stability of the direction of movement $y_d(t)$ and braking $y_b(t)$, the stability of the dynamic properties $w(t)$ (*Figure 2*). In this case, the critical values of these parameters, which are in the area of the *AF* functioning (*Figure 3*), are selected according to experimental data based on the method of partial accelerations (*Artiomov et al., 2025*), which is effectively used in assessing the dynamic properties and stability of vehicles (*Abramov et al., 2014*).

Using the standard form of recording the variable state of a grain truck, we consider its movement as the movement of an autonomous dynamic system when the forces of resistance to movement and the amount of energy used for movement change. This influence usually causes a change in the speed $v(t)$ of translational motion, which is characterised by equation (*Bilokon & Okocha, 2002*)

$$\frac{dv(t)}{dt}=\frac{P_k-\sum R_c}{m_{ag}}, \tag{19}$$

where

Pk is the moving force of the unit (tangential traction force),

ΣR_c is the sum of the forces of resistance to the movement of the unit,

m_{ag} is the reduced mass of the unit.

Discussion

The forces of resistance to the movement of a grain carrier during operation depend on factors, many of which are variable, such as terrain, speed, instability of the mass of transported grain, etc. As the drag forces change, the dv/dt changes during grain transport. Measurement of the acceleration dv/dt requires the use of appropriate metrological support for measuring and registration complexes that will allow determining its kinematic and dynamic parameters without interfering with the design of the grain truck (*Lebedev et al., 2018*). The basis of this complex is capacitive semiconductor three-axis acceleration sensors—accelerometers, which are installed on the car and trailer of the grain truck to assess longitudinal and lateral accelerations.

The combination of the acceleration sensors with the KrAZ-6511C4 navigation system allows to receive on-line and archive information, the analysis of which provides reliable data on the route and modes of movement of the grain truck, instant and average fuel consumption and direction of movement.

To ensure that the grain carrier operates in the optimal range, it is necessary to select such nominal values of functional parameters and their tolerance fields that ensure the position of the spreading and outlet fields in this range.

Conclusions

The study of the functional adaptation of a grain truck with an unstable mass of transported grain revealed that fluctuations in the grain load during transportation significantly affect the stability of the vehicle, especially during manoeuvring and braking. When estimating the weight of a grain truck, it is necessary to consider the density of the transported grain. The dependence of the volumetric carrying capacity of a grain truck is estimated by the parameters of nominal carrying capacity, volumetric carrying capacity, body volume, and cargo volume.

The dynamic space of grain truck operation is based on the metric state space, each element of which fully determines the state of the system under consideration according to certain functional parameters. If one or more functional parameters of a grain truck are unstable and deviate from their nominal values, the grain truck may lose its functional stability, in which case it will not perform the functions defined by the regulatory and technical documentation. In this case, the dynamic space of grain carrier operation is determined by transfer functions.

During the operation of a grain carrier, the task of ensuring its operation in one of two areas is solved: the area of operation in which the grain carrier operates according to its intended purpose (ensuring the required traction force, stability of the direction of movement and braking, etc.); the area of optimal operation, e.g., according to the energy saving criterion, in which the grain carrier operates at an acceptable change in speed (change in acceleration within acceptable limits). To ensure that the grain carrier operates in the optimal range, it is necessary to select such nominal values of functional parameters and their tolerance fields that ensure the position of the spreading and outlet fields in this range.

Conflict of interest

The authors declare that there is no conflict of interest.

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Appendix

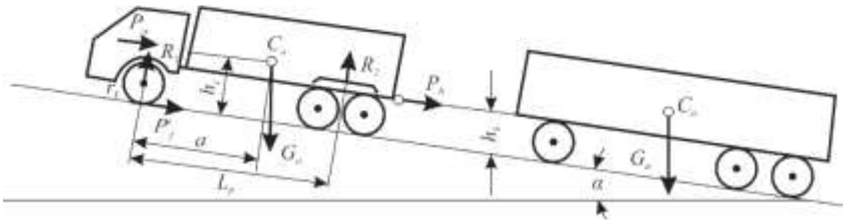

Figure 1. Diagram of the forces acting on a grain truck when driving uphill with an angle α

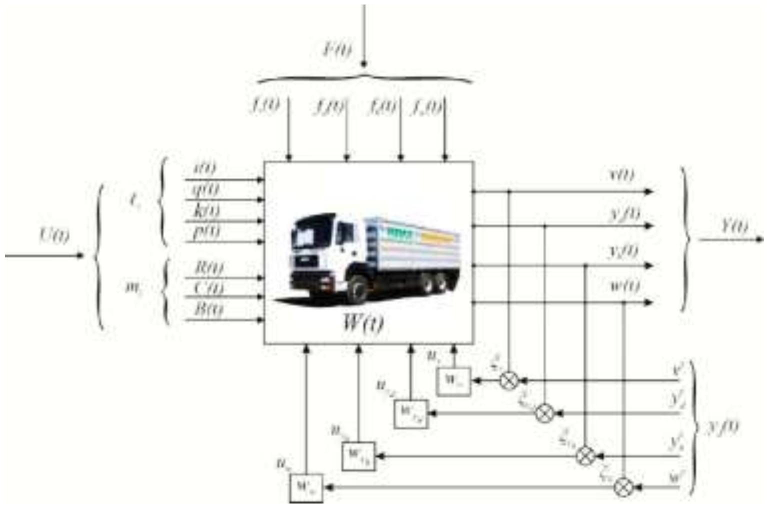

Figure 2. Representation of a grain truck as a multidimensional system in a variable state

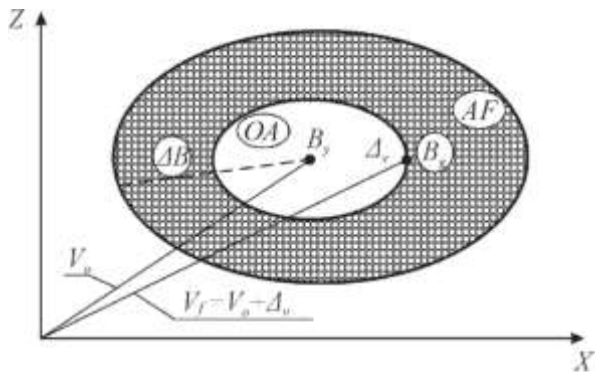

Figure 3. Correlation of the areas of optimal operation OA of the grain carrier and the functioning

Table 1. Bulk density of grain crops

№	Name of grain crop	Density, kg/m^3
1	Wheat	750-850
2	Barley	600-750
3	Oats	400-550
4	Rye	700-750
5	Millet	700-850

Table 2. Results of operational tests of the «Karavan-2» road

Tests	Mileage of the road train during testing, km	Transported cargo, cargo weight, t	«Shoulder» of routes, km	Average fuel consumption, l/10 km	Gear ratio of the main gear
1	Total 2505 With cargo 1250	Corn grain, 48, 83–52, 66 Sunflower seeds, 27, 66	87–89 182–194	53,0–54,6 42,0–42,1	i_{mg} = 6,154
2	Total 2100 With cargo 1050	Corn grain, 41,72–47,01	66–69	48,2–50,1	
3	Total 1737 With cargo 857	Corn grain, 48,7	857	42,0–43,1	i_{mg} = 4,9
4	Total 1340 With cargo 560	Wheat grain, 40,1	280	37,8–38,0	
5	Total 1320 With cargo 225	Organic mix, 35,0 Organic mix, 54,0	115 110	35,0–35,3 40,0–42,3	