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EVALUATION OF THE STRENGTH OF THE TRACTOR FRAME UNDER EMERGENCY BRAKING CONDITIONS

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Abstract

Authors carried out a theoretical study of the force impact during emergency braking on the strength of the frame of a truck tractor as a part of a road train with a semi-trailer in order to build a model of the dependence of the safety factor index of the frame on the geometric and weight parameters of the car, semi-trailer, transported cargo and the type of the pavement. Using D'Alembert's principle, a generalized calculation scheme of the frame of the semi-trailer and the truck unit after reaching a steady deceleration during emergency braking while maintaining straight-line movement and adhesion of all wheels to pavement was made. Through a static calculation, the dependences for the unknown reactions of the car frame constraints were obtained, its dangerous cross-section was established, and the condition for the static strength of the longeron was determined. Using this condition and the obtained ratios for active and reactive loads, a model of the dependence of the safety margin coefficient of the car frame on the road train parameters was built. By the example of a road train consisting of a KrAZ-6446 truck tractor and a VARZ-6006 semi-trailer the application of the constructed model for evaluating the strength of the car frame and determining the permissible safe zone location of the center of gravity of different weights cargo in the plane of the road train is demonstrated. The method proposed in this work and the built model can be used to study the strength of the frames of truck tractors and semi-trailers of other manufacturers and types and to establish safe schemes for the placement and fastening of loads to ensure the operational reliability of the vehicle and the safety and security of cargo transportation.

Keywords: road train; emergency braking; tractor unit; frame; strength

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1. Introduction

Modern freight road transport, in particular road trains, is an integral part of the freight transportation system, the importance of which is growing globally. In particular, in Ukraine, due to changes in logistical transport flows during martial law, wheeled road transport plays a special role. Along with increasing efficiency, one of the important and urgent directions of improvement of road freight transport is increasing its reliability and improving the safety of operation. The problem of ensuring the reliability and safety of freight road transport is multifactorial, which leads to a wide range of research directions, while the general framework of requirements for the vehicle during operation is established by legislation.

One of the vital components of the operational reliability of road transport is safe braking [1]. For freight transport, the mass of which can fluctuate within significant limits, the braking process is less predictable and depends on a larger number of parameters [2].

Several directions of research into the braking process of freight road transport and ensuring its reliability are depicted in well-known scientific works. Among them: analytical modeling of the braking process [2, 8] and individual elements of the braking system [9], use of specialized software for computer modeling [5, 7], experimental studies of the influence of freight transport parameters on the braking process, for example [3, 4, 10] and some of its aspects, for example [6, 11], development and improvement of braking systems [9, 12], research of the braking impact on cargo maintenance [13–15]. It should be noted that the majority of the scientific works are devoted, in particular, to experimental studies of the braking process. Among them: a study of the load distribution on the vehicle's axles during braking [4, 16], the influence of the size and placement of the cargo on the braking distance and its duration [1, 3], experimental evaluation of the braking systems' effectiveness [10, 17, 18], a study of the load extent acting on the cargo during the braking process [15], a study of the influence of various factors on the adhesion of tires with the road surface [6, 11], a study of the brake system's wear influence on the braking process [19].

Experimental studies and computer modeling provide an accurate picture of the correlation between braking parameters and particular parameters of the vehicle during specific tests. However, a general analysis of the braking process and the identification of ways to improve it requires the development of analytical models for the movement and braking of certain vehicles. For example, in [2], we can see a built analytical model of the road train braking, which includes a quasi-static model of the linear movement of the road train, a model of the braking system, and a modified Burckhardt model for the adhesion of the tires with the road surface. Using this model in particular, a significant influence of the weight and location of the cargo's center of gravity on braking safety was established and confirmed by experimental studies.

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A separate, but important type of freight transport braking is emergency braking. Emergency braking is executed by using the working brake system with maximum intensity, therefore the deceleration during emergency braking is several times greater than the deceleration during regular braking. This causes significant dynamic loads on the elements of freight transport. In the case of the tires' low adhesion coefficient with the road surface, emergency braking can cause a dangerous phenomenon of jackknifing [8]. In some cases, emergency braking can be avoided by changing the traffic lane, but such a maneuver is dangerous for the road train due to the risk of rollover due to the high center of mass [20].

Significant dynamic loads during emergency braking cause a significant load redistribution between the axles of the road train, which reduces the efficiency of the braking system, due to a decrease in the adhesion coefficient of the tires with the road surface [6, 11]. The significant influence on this is the size and location of the cargo [10, 16, 18]. With improper fastening [13, 15] and bulk cargo [4] additional redistribution of the load on the road train axles may occur due to cargo displacement during emergency braking.

Another aspect of the load redistribution on the freight transport's axles during emergency braking is the change of loads on the tractor unit frame, which can cause a decrease in the safety margin of the vehicle frame up to its destruction. However, this issue remains poorly researched. Therefore, the purpose of the presented work lies in a theoretical study of the force effect on the strength of the car frame during the emergency breaking of a freight road train as part of a tractor unit and a semi-trailer.

The analytical modeling method was chosen for our study of this issue. The analytical approach to evaluating the strength of the car frame is less accurate compared to detailed finite-element models (FEM) [21–23], which allow more accurate determination of the stress-strain state. FEM analysis is indispensable when performing verification calculations of the specific car frame, however, for the analysis and study of general dependencies, the method of analytical modeling is more convenient.

2. Materials and Methods

During emergency braking, the road train is moving with deceleration. Let's assume that during braking the road train continues to move in a straight line, the axes of the frame of the car and the semi-trailer and the center of gravity of the load lie in the same plane that coincides with the line of movement, the load is rigidly connected to the platform of the semi-trailer and does not change its position, the mass of the moving road train remains constant m_{stt}. Then, after the start of emergency braking, according to the D'Alembert principle, and using the Amontons–Coulomb law, the equation of motion is:

$am_{stt} = fgm_{stt}$, from where

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$$a = fg\,. \tag{1}$$

where f – coefficient of adhesion of automobile tires with the pavement; g – acceleration of gravity.

Ratio (1) shows that the amount of maximum deceleration a during emergency braking does not depend on the speed of movement before the start of braking. Thus, inertial forces can have a maximum value even when braking occurs at a relatively low speed of the road train.

To assess the strength of the car frame, it is necessary to establish its loads during emergency braking, which include active, like inertial forces, the weight of the car and trailer with the cargo, and reactive, like frictional forces between the tires and the pavement and its reaction to the tire pressure. The latter are unknown and can be established using theoretical mechanics.

The scheme of the loads shown in Figure 1 was used as the basis for the calculation of the force flow on the frame structures of the road train containing a truck tractor and two-axle semi-trailer in emergency braking mode.

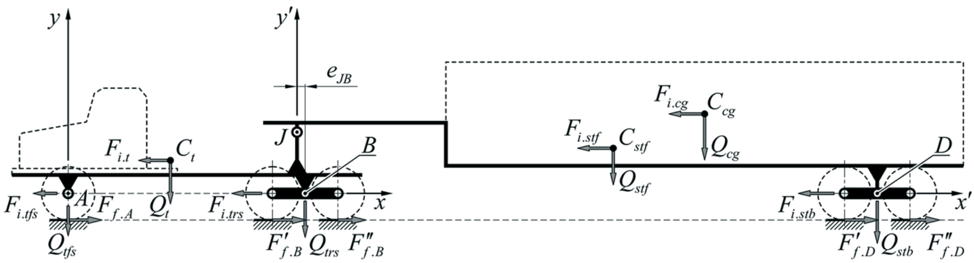

Fig. 1. Scheme of the loads acting on the road train during braking

During braking on the frame structures of the road train components act loads from the car's parts and joints own weight (Q_t, Q_{tfs}, Q_{trs}), semi-trailer (Q_{stf}, Q_{stb}) and cargo (Q_{cg}), the friction force between the tires and the pavement ($F_{f.A}$, $F'_{f.B}$, $F''_{f.B}$, $F'_{f.D}$, $F''_{f.D}$) and, according to D'Alembert's principle, inertial forces of progressively moving masses of the car ($F_{i.t}$, $F_{i.tfs}$, $F_{i.trs}$) and the loaded trailer ($F_{i.stf}$, $F_{i.stb}$, $F_{i.cg}$), which are directed opposite to the direction of movement change (Figure 1). The forces of weight and inertia and their application points can be established according to the passport data of the car and semi-trailer. However, the friction forces depend on the unknown reactions of the tire pressure of the road train on the pavement, for determining which it is necessary to carry out a compatible static calculation of the frame of the semi-trailer and the car.

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3. Results

The scheme of loads acting on the semi-trailer frame is shown in Figure 2. Let's divide the reactive load transmitted from the car to the trailer frame through the hinge J of the coupling device into horizontal H_J and vertical V_J components. The forces of friction between the tires of the rear suspension of the trailer and the pavement, as well as the pavement reaction from the cart, are transmitted to the hinge D – the axis of the balancer, in the form of horizontal H_D and vertical V_D components of the full reactive load. Also, the braking moment is transmitted to the trailer frame through track rods $M_{f.D}$.

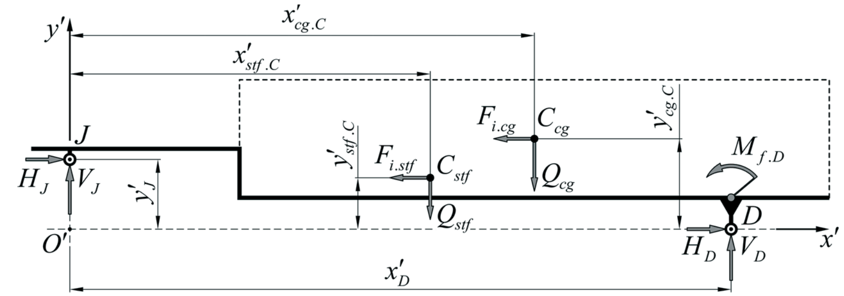

Fig. 2. Diagram of forces acting on the trailer frame during braking

The horizontal component of the support reaction D consists of the braking forces of friction $F'_{f.D}$ and $F''_{f.D}$ of the trailer tires against the pavement and the inertia force $F_{i.stb}$ of the trailer's wheeled cart (fig. 2):

$$H_D = F'_{f.D} + F''_{f.D} - F_{i.stb}, \tag{2}$$

The friction forces $F'_{f.D}$ and $F''_{f.D}$ will obviously be different, but their sum must be equal to:

$$F'_{f.D} + F''_{f.D} = f\left(V_D + m_{stb}g\right), \tag{3}$$

where f – coefficient of adhesion of automobile tires to the pavement; m_{stb} – the mass of the wheeled cart of the trailer; g – acceleration of gravity.

The inertia force $F_{i.stb}$ of the trailer's wheeled cart depends on the amount of deceleration a and according to (1) during emergency braking equals:

$$F_{i.stb} = m_{stb}a = m_{stb}fg\ . \tag{4}$$

Taking into account (3) and (4), expression (2) for the horizontal component of the reaction support H_D:

$$H_D = fV_D, \tag{5}$$

The braking moment $M_{f.D}$ was approximately determined as the moment of friction forces $F'_{f.D}$ and $F''_{f.D}$ relative to the axis of the balancer $M_{f.D} = R_{w.st}\left(F'_{f.D} + F''_{f.D}\right)$, or taking into account (3)

$$M_{f.D} = R_{w.st} f\left(V_D + m_{stb} g\right), \tag{6}$$

where $R_{w.st}$ – the radius of the trailer wheels.

According to the diagram in Figure 2 equilibrium conditions of a semi-trailer with a load connected to a car during braking will be written as follows:

$$\left.\begin{aligned}
&\sum M_{iC} = \left[-Q_{stf} x'_{stf.C} - Q_{cg} x'_{cg.C}\right] + \left[F_{i.stf}\left(y'_{stf.C} - y'_J\right) + F_{i.cg}\left(y'_{cg.C} - y'_J\right)\right] + V_D x'_D + H_D y'_J + M_{f.D} = 0;\\
&\sum M_{iD} = \left[Q_{stf}\left(x'_D - x'_{stf.C}\right) + Q_{cg}\left(x'_D - x'_{cg.C}\right)\right] + \left[F_{i.stf} y'_{stf.C} + F_{i.cg} y'_{cg.C}\right] - V_J x'_D - H_J y'_J + M_{f.D} = 0;\\
&\sum F_{ix} = H_J - F_{i.stf} - F_{in.cg} + H_D = 0,
\end{aligned}\right\} \tag{7}$$

where Q_{stf}, $F_{i.stf}$ – weight and inertia force of the trailer frame; Q_{cg}, $F_{i.cg}$ – weight and inertia force of the load; $x'_{stf.C}, y'_{stf.C}; x'_{cg.C}, y'_{cg.C}$ – coordinates of the centers of gravity of the trailer frame and cargo in the coordinate system $x'O'y'$ (fig. 2); y'_J, x'_D – coordinates of points J and D.

The weight and inertia force of the trailer frame and the load, taking into account (1), will be equal to:

$$Q_{stf} = m_{stf} g,\ F_{i.stf} = m_{stf} fg;\ \ Q_{cg} = m_{cg} g,\ F_{i.cg} = m_{cg} fg, \tag{8}$$

where m_{stf}, m_{cg} – the weight of the trailer frame and the load, respectively.

By solving system (7) concerning unknown forces V_D, V_J, H_J, taking into account (5), (6) and (8), it is obtained that:

$$V_D = \frac{g m_{cg}\left(x'_{cg.C} - f y'_{cg.C}\right)}{x'_D + f h'_J} + g\left(m_{st\Sigma} - m_{stb}\right) - F_{st1},\ \ V_J = F_{st1} - \frac{g m_{cg}\left(x'_{cg.C} - f y'_{cg.C}\right)}{x'_D + f h'_J},\ \ H_J = fV_J, \tag{9}$$

where we entered notations:

$$F_{st1} = g\frac{m_{st\Sigma}\left(x'_D + fR_{w.st}\right) - m_{stf}\left(x'_{stf.C} - f y'_{stf.C}\right) - m_{stb} x'_D}{x'_D + f h'_J},\ \ m_{st\Sigma} = m_{cg} + m_{stf} + m_{stb},\ \ h'_J = y'_J + R_{w.st}. \tag{10}$$

The determination of the components V_J and H_J in the supporting hinge J, connecting the semi-trailer with the car, allows us to proceed to the determination of the loads acting on the car frame. The calculated diagram of the tractor unit frame is shown in Figure 3.

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Frictional forces between the tires of the front suspension of the car and the pavement, as well as its reaction, that are transmitted to the car frame, are reduced to the wheel joint A in the form of components H_A and V_A.

The horizontal component of the reaction support A consists of the friction force $F_{f.A}$ of the front suspension tires on the pavement and the inertia force $F_{i.tfs}$ of the front suspension of the car (Figure 1). Taking into account (1), we've got:

$$H_A = F_{f.A} - F_{i.tfs} = fV_A. \tag{11}$$

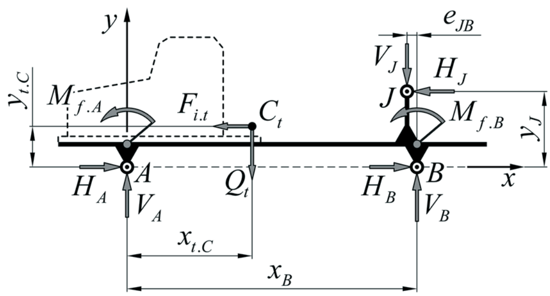

Fig. 3. Calculation scheme of the car frame as part of the road train

Through the fastening of the springs, the braking moment $M_{f.A}$ is transmitted to the frame, which is decided as equal to the moment of frictional forces relative to the hinge A:

$$M_{f.A} = R_{w.t}F_{f.A} = R_{w.t}f\left(V_A + m_{tfs}g\right), \tag{12}$$

where $R_{w.t}$ – radius of the car wheel; m_{tfs} – mass of the front suspension of the car.

From the interaction of the rear suspension tires with the pavement during braking, forces V_B and H_B and braking torque $M_{f.B}$ are transmitted to the car frame through springs and track rods:

$$H_B = fV_B, \quad M_{f.B} = R_{w.t}f\left(V_B + m_{trs}g\right), \tag{13}$$

where m_{trs} – mass of the rear suspension of the car.

Equilibrium conditions of a car in a road train during braking according to the calculation scheme in Figure 3:

$$\left.\begin{aligned}&\sum M_{iA}=-Q_t x_{t.C}+F_{i.t}y_{t.C}+V_B x_B+H_J y_J-V_J\left(x_B-e_{JB}\right)+M_{f.A}+M_{f.B}=0;\\&\sum M_{iB}=-V_A x_B+Q_t\left(x_B-x_{t.C}\right)+F_{i.t}y_{t.C}+H_J y_J+V_J e_{JB}+M_{f.A}+M_{f.B}=0;\\&\sum F_{ix}=H_A+H_B-F_{i.t}-H_J=0,\end{aligned}\right\}\tag{14}$$

where Q_t, $F_{i.t}$ – weight and inertia force of the car; $x_{t.C}, y_{t.C}$ – coordinates of the car's center of gravity; y_J, x_B – coordinates of points J and B; e_{JB} – horizontal eccentricity between the axis (p. B) of the balancer of the rear suspension of the car and the hinge of the coupling device (p. J).

The weight and inertia force of the car, taking into account (1), will be equal, respectively:

$$Q_t=m_t g,\ F_{i.t}=m_t fg\,,\tag{15}$$

where m_t – vehicle weight (not including the weight of the front and rear suspensions).

The solution of system (14) concerning the unknown forces V_A, and V_B, taking into account (11), (12) and (13), is obtained:

$$V_A=V_J\frac{e_{JB}+fh_J}{x_B}+m_t g-F_{t1},\quad V_B=V_J\frac{x_J-fh_J}{x_B}+F_{t1}\,,\tag{16}$$

where we entered notations:

$$F_{t1}=\frac{g}{x_B}\left[m_t\left(x_{t.C}-fy_{t.C}\right)-fR_{w.t}m_{t\Sigma}\right],\ \ m_{t\Sigma}=m_t+m_{tfs}+m_{trs},\ \ h_J=y_J+R_{w.t}\,.\tag{17}$$

Ratios (5), (6), (9), (11)–(13) and (16) make it possible to determine the amount of reactive loads of the road train that occur during emergency braking. Together with the active weight load and inertial forces, they allow us to determine the internal force factors in the frame elements of the truck and semi-trailer and to evaluate their strength in this mode of operation of the road train.

During emergency braking, the frame of a truck is in more dangerous conditions than the frame of a semi-trailer, so we will focus further on evaluating the strength of the car frame.

The calculation diagram of the rear part of the car frame is shown in Figure 4. The relatively small distributed load from the frame's weight is neglected here.

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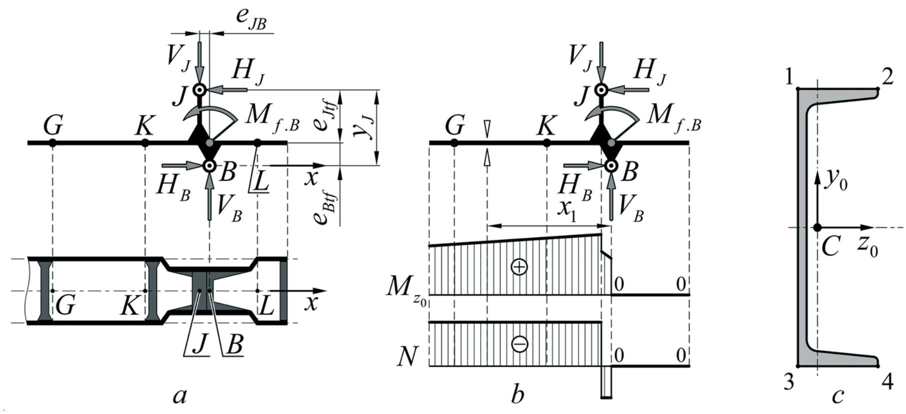

Fig. 4. Calculation diagram of the dangerous section of the car frame (a, b) and cross-section diagram of the longeron (c)

According to the calculations made on the example of a road train consisting of a KrAZ-6446-076-02 truck and a two-axle semi-trailer VARZ-6006, the shear and moment diagrams of internal force factors in the cross-sections of the dangerous zone of the frame near the hinge B were built (Figure 4b). It is here that the maximum values of the bending moment M_z and longitudinal force N occur. However, this section of the frame is additionally strengthened by stiffening ribs, cross-bars, and elements of attachment of the coupling device and the wheeled cart. Therefore, the dangerous estimated cross-section of the car frame during emergency braking is the cross-section K located in front of the reinforced section of the frame.

The location of the longerons as to the points of load reduction indicates that the longerons on the section GK during braking of the road train work on the combined effect of lateral bending and off-center torque tension. However, the stiffness of the reinforced section KL must absorb the torque and bending moment transmission to the longeron section GK in the plane of the frame. Accordingly, in the section K of the longeron, the internal force factors are equal to:

$$N_K = -\frac{1}{2}H_J + \frac{1}{2}H_B;\;\; M_{z_0K} = -\frac{1}{2}V_J\left(x_K - e_{JB}\right) + \frac{1}{2}H_J e_{Jtf} + \frac{1}{2}M_{f.B} + \frac{1}{2}V_B x_K + \frac{1}{2}H_B e_{Btf}, \quad (18)$$

The cross-section of the longeron of a truck has the shape of a structural channel (Figure 4c), accordingly, for the considered type of deformation (18), the dangerous points of the cross-section K are the extremely compressed fibers of the top flange, in which the normal stresses will be equal to:

$$\sigma_{K,1-2} = \frac{|N_K|}{A} + \frac{|M_{z_0K}|}{W_{z_0}}, \tag{19}$$

where A, W_{z_0} – area and moment of resistance of the cross-section of the longeron.

In the case of beams made of rolled profiles, the local stability check is not required, since the profiles of the rolled steel assortments are designed with the condition of equality of critical stresses and calculated resistance of the material. Therefore, local loss of stability of longeron elements can occur after reaching the yield point of its material. At the same time, reaching the yield point at individual points of the structural element means the appearance of irreversible plastic deformations, which means a loss of strength for the engineering structure. Therefore, the static strength of the longerons of the car frame must be determined relative to the yield point σ_f of the material, as the limit value of stresses.

$$\frac{|N_K|}{A} + \frac{|M_{z_0K}|}{W_{z_0}} \le \frac{\sigma_f}{n}, \tag{20}$$

where n – the safety factor of the longeron.

Ratios (9), (13), (16), (18), and (20) make up the dependence model of the safety factor of the frame of the tractor unit as part of a road train with a semi-trailer, under conditions of emergency braking, on the weight and geometric parameters of the road train, mass and the center of mass position of the cargo, the type and condition of the pavement. These ratios can be combined into a single inequation:

$$\left(F_{st1} - \frac{gm_{cg}\left(x'_{cg.C} - fy'_{cg.C}\right)}{x'_D + fh'_J}\right)\left(\frac{fk_1}{A} + \frac{l_1}{W_{z_0}}\right) + \frac{m_{trs}gfR_{w.t}}{W_{z_0}} - F_{t1}\left(\frac{f}{A} - \frac{l_2}{W_{z_0}}\right) \le \frac{2\sigma_f}{n}, \tag{21}$$

where we entered notations

$$k_1 = \frac{e_{JB} + fh_J}{x_B},\ l_1 = fe_{Jtf} + e_{JB} + f\left(R_{w.t} + e_{Btf}\right)\frac{x_J - fh_J}{x_B} - \frac{e_{JB} + fh_J}{x_B}x_K,\ l_2 = x_K + fe_{Btf} + fR_{w.t}. \tag{22}$$

Inequation (21) shows that the coordinates $x'_{cg.C}$, $y'_{cg.C}$ of the center of gravity of the load on the semi-trailer are among the important parameters that affect the strength of the truck frame in the road train. It is impossible to rule out the possibility of a dangerous situation, when with the normative weight of the cargo, due to its unfavorable location on the semi-trailer, emergency braking can lead to the destruction of the car frame.

Model (21) allows you to set the permissible location of the center of gravity of the load m_{cg} on the semi-trailer, for which the necessary safety factor n of the truck frame will be ensured:

$$x'_{cg.C} \ge fy'_{cg.C} + \frac{x'_D + fh'_J}{gm_{cg}}\left(F_{st1} - \frac{nF_{t1}\left(fW_{z_0} - Al_2\right) - nAm_{trs}gfR_{w.t} + 2\sigma_f AW_{z_0}}{n\left(fk_1W_{z_0} + Al_1\right)}\right). \tag{23}$$

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4. Discussion

Let's consider the application of the built model on the example of a road train consisting of a KrAZ-6446-076-02 truck [21] and a two-axle semi-trailer VARZ-6006 in the conditions of emergency braking on a dry asphalt-concrete surface: $f = 0.8$. The maximum weight of cargo that can be transported on the VARZ-6006 semi-trailer according to the technical manual is $m_{cg\max} = 60\,t$.

The geometric and weight characteristics of the car and the semi-trailer were determined according to the data in the technical references:

$$\begin{gathered} R_{w.t} = 0.592m,\ \ x_{t.C} = 1.77m,\ \ y_{t.C} = 1.26m,\ \ y_J = 1.02m,\ \ x_B = 5.3m,\ \ e_{JB} = 0.18m, \\ x_K = 0.78m,\ \ e_{Jtf} = 0.635m,\ \ e_{Btf} = 0.385m;\ h_J = 1.612m \\ m_t = 6491kg,\ \ m_{tfs} = 1675kg,\ \ m_{trs} = 3234kg,\ \ m_{t\Sigma} = 11400kg; \end{gathered} \tag{24}$$

$$\begin{gathered} R_{w.st} = 0.505m,\ \ x'_{stf.C} = 7.27\,m,\ y'_{stf.C} = 0.69\,m,\ \ y'_J = 1.18m,\ \ x'_D = 10.13m,\ \ h'_J = 1.685m; \\ m_{stf} = 13000\,kg, m_{stb} = 5000kg. \end{gathered}$$

The radius of the wheels here was taken as the static radius of the tires.

The mass m_{cg} of the cargo, as well as the coordinates of its center of gravity $x'_{cg.C}$, $y'_{cg.C}$, were left as variable parameters. According to the technical documentation, the longerons of the car frame are made of hot-rolled structural channel №30B-1 (DSTU 7551:2014) (fig. 5) of 15KHSND steel (DSTU 8541:2015) with strength class 345.

Geometric characteristics of the longeron profile according to DSTU 7551:2014:

$$A = 49.88\,cm^2,\quad W_x = 433.03\,cm^3\,. \tag{25}$$

The yield point of the rolled steel with strength class 345 according to DSTU 8541:2015 and the safety factor index of the car frame is:

$$\sigma_f = 345\,MPa,\quad n = 3\,. \tag{26}$$

After substituting the values (24)-(27) into (10), (17), (22), and (23) we get:

$$x'_{cg.C} \geq 0.8y'_{cg.C} + 10.544 - \frac{98674.66}{m_{cg}}\,. \tag{27}$$

According to (27), graphs $y'_{cg.C} = y'_{cg.C}\left(x'_{cg.C}\right)$ (Figure 5) were drawn for different values of the weight of the cargo on the semi-trailer $m_{cg} = 10\,t,\ 20\,t,\ 30\,t,\ 40\,t,\ 50\,t,\ 60\,t$.

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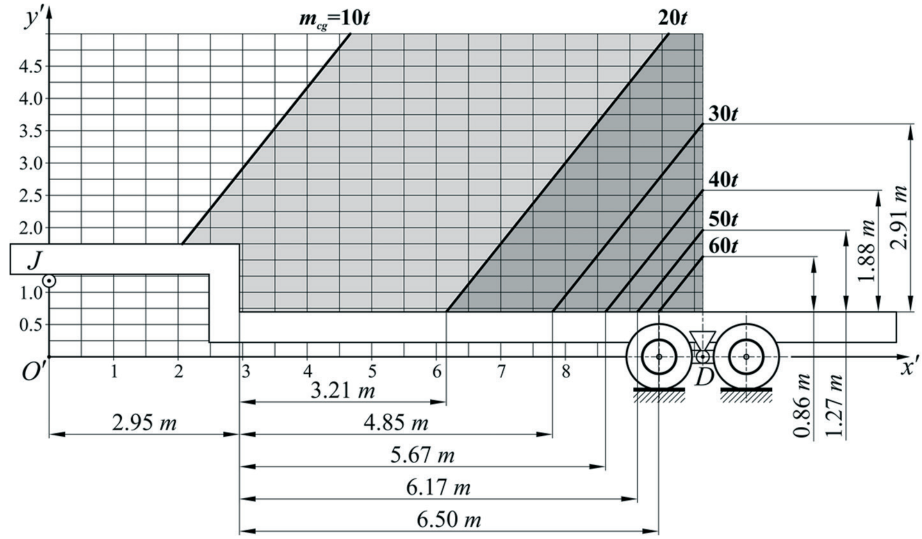

Fig. 5. Graphs of the dependence of the permissible coordinates of the location of the center of gravity of cargo of different weights on the VARZ-6006 semi-trailer connected to the KrAZ-6446-076-02

Graphs in Figure 5 allow us to set the recommended horizontal position of the cargo's corresponding mass on the semi-trailer, given the known position of its center of gravity. To ensure the accepted index of safety factor $n = 2$ of the KrAZ-6446-076-02 frame longerons, the center of gravity of the given mass load must be below and left of the corresponding line in Figure 5.

According to Figure 5 location of the cargo $m_{cg} \leq 10\,t$ center of gravity is practically not limited by the working surface of the semi-trailer. At the same time, the location of the cargo, even of medium, for the VARZ-6006 semi-trailer, weight $m_{cg} = 30\,t$, already has quite significant limitations. Further, for the maximum passport load $m_{cg} = 60\,t$, there is only a small area of permissible location of the center of gravity near the axle of the semi-trailer's wheeled cart.

According to the technical manual, the KrAZ-6446-076-02 truck allows a load on the fifth-wheel coupling up to $170\,kN$. The calculations for the case of $m_{cg} = 50\,t$, $x'_{cg.C} = 7\,m$, $y'_{cg.C} = 2.5\,m$ show that in the mode of uniform motion, a vertical load $154\,kN$ will act on the fifth-wheel coupling, which is permissible according to the vehicle's passport data. However, in the emergency braking mode, the vertical load on the fifth-wheel coupling, calculated according to (9) will be $V_J = 281\,kN$, and the safety factor index, according to (21), will decrease to $n = 0.96$, which means the complete exhaustion of the carrying capacity of the car's longerons and the risk of their destruction.

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5. Conclusions

We conducted a theoretical study of the force effect on the strength of the frame of a tractor unit being a part of a road train with a semi-trailer during emergency braking. The obtained ratios were used to build an analytical model (21), which connects the geometric and weight parameters of the tractor unit and a semi-trailer, the mass and location of the center of gravity of the transported cargo, the coefficient of adhesion of the tires with the pavement, the geometric characteristics of the cross-section of the longeron of the car frame, yield point of its material and the safety factor of the frame. The application of the constructed model is demonstrated in the example of a road train consisting of a KrAZ-6446-076-02 tractor unit and a VARZ-6006 two-axle semi-trailer. This specific example shows that a load that, in the mode of uniform movement, creates a load on the fifth-wheel coupling of the car within the normative limits, during emergency braking can create an excessive load, which can lead to mechanical destruction of the tractor unit's frame. Also, the application of the built model for the development of recommendations for the center of gravity's safe location for loads of different weights, which ensures the given safety factor index of the car frame during emergency braking mode, is shown in the example of the mentioned road train.

The research methodology and built model, presented in this work, can be used to assess the strength of the frames of automobile tractor units and semi-trailers of the considered type, and to establish safe schemes for the location of loads of different weights on the trailers of road trains in the emergency braking mode, to ensure the strength of the tractor units' frames and the safety of freight transport in general.

6. References

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