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STUDY OF THE DYNAMICS OF TRUCK MOVEMENT ACROSS A BRIDGE CROSSING

Summary. This paper is the first comprehensive study of the dynamics of truck movement across a bridge crossing with defects on a road surface. A mathematical model of the dynamics of the truck movement across the bridge crossing is obtained. To confirm the adequacy of the proposed mathematical model, a comparative analysis of the results of theoretical and experimental studies was carried out. This approach makes it possible to determine the nature of the distribution of dynamic loads in areas where truck wheels contact with the road surface of the bridge crossing. This research was carried out within the framework of the project "Development of a load model based on the actual parameters of heavy rolling stock to determine the carrying capacity of road bridges during their restoration and operation in the war and post-war periods" under the competition "Science for the Reconstruction of Ukraine in the War and Post-War Periods" at the expense of grant support from the National Research Foundation of Ukraine.

1. INTRODUCTION

During construction and operation, bridges are constantly exposed to forces. Among these forces, dynamic loads from heavy vehicles deserve special attention. The consequences of dynamic loading on bridges can include structural fatigue, accelerated deterioration, and, in extreme cases, even failure. Studies show that repeated loads from trucks can lead to the initiation and propagation of cracks in the bridge's structural elements, which poses a danger to road users.

This problem is especially relevant for bridges that have experienced physical deterioration during operation. Studies on the topic of traffic load on short-span bridges were conducted in [1-3], in particular, taking into account the dynamics [4-6], as well as on large bridges [7-9].

Dynamic loading is influenced by various factors, including vehicle speed, design parameters, and road surface conditions. Each of these factors affects the magnitude and frequency of forces transmitted to the bridge, thereby affecting its stress-strain state and durability [10-12].

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The weigh-in-motion (WIM) system is used to determine the load from a vehicle in motion. However, the accuracy of weighing data in motion is usually much lower than for static scales [11]. If the static weighing method can give an error of 1%, then the sensors of WIM systems have an accuracy of about 5–10% at best [12].

Advances in computational modeling and simulation techniques have allowed engineers to better predict the behavior of bridges under dynamic loading conditions. For example, finite element analysis allows for virtual testing of bridge structures, taking into account factors such as material properties, geometric configurations, and loading scenarios [13].

The DIVINE (Dynamic Interaction between the Vehicle and Infrastructure Experiment) project (OECD, 1997) is considered the most comprehensive study of the dynamic load from trucks. According to the results of the DIVINE study, the influence of vehicle suspension on the dynamic wheel load and the magnitude of the response of bridge elements was not very significant in the case of a smooth bridge profile and approaches on medium-length bridges. It was also found that the dynamic component depends on the vertical dynamics of the vehicle – including factors such as the mass distribution and stiffness of the vehicle structure, the mass distribution of the payload, suspension, and tires – as well as the longitudinal profile of the road surface and the vehicle speed. The conclusions of this study serve as a basis for the development of requirements for road-friendly suspension (RFS) and the subsequent introduction of higher mass limits (HML) for heavy vehicles in Australia [14].

By modeling the dynamic response of bridges to different traffic conditions, engineers can optimize their designs to improve performance and durability. WIM systems are used mainly outside of bridge crossings, the high cost of such systems, and the technical and economic inexpediency of installing them on all bridges. Therefore, it is relevant to use the mathematical model of the dynamics of truck movement across a bridge crossing proposed by the authors, which makes it possible to study the dynamic load acting between the wheels of the truck and the road surface of the bridge crossing.

Taking into account the analysis, there is a need to study in full-scale conditions the effect of dynamic loads acting between the wheels of a truck and the pavement of a bridge crossing. The purpose of this study is to examine the dynamics of a truck's movement across a bridge crossing and determine the dynamic load acting between its wheels and the pavement of the bridge crossing, including the presence of a pothole.

To achieve this goal, the following tasks need to be carried out:

1. Study and build a profile of the pavement of the bridge crossing;
2. Record the nature of the truck's movement across the bridge;
3. Propose a mathematical model of the dynamics of the truck's movement across the bridge;
4. Formulate initial and boundary conditions for calculations based on the mathematical model of the dynamics of the truck's movement across the bridge;
5. According to the proposed mathematical model, conduct theoretical studies of the dynamics of the truck's movement across the bridge;
6. Confirm the adequacy of the mathematical model;
7. According to the proposed mathematical model, carry out theoretical studies of the dynamic loads acting between the wheels of the truck and the bridge with a road surface defect.

2. CONDUCTING EXPERIMENTAL STUDIES OF THE DYNAMICS OF TRUCK MOVEMENT ACROSS A BRIDGE CROSSING

Experimental studies are conducted in two stages. The first is the study of the real profile of the bridge crossing pavement; the second is the study of the nature of truck movement while crossing the bridge.

The objects of the research are a bridge crossing over the Rakuv River on the international public road M-11 "Lviv – Shehyni" (a single-span bridge with a length of 12 m); and a MAN TGL 12.220 truck.

The first stage of the experimental research involved a technical leveling of the bridge pavement (Fig. 1) with a step of 1 m.

Fig. 1. Leveling of the road pavement profile of the bridge with a step of 1 m

The leveling results were analyzed and processed. The dependence of the change in the vertical q_z coordinate of the road surface of the bridge crossing on its horizontal q_x coordinate was obtained (Fig. 2). The analysis of the leveling results shows that the longitudinal profile of the bridge has a slight (about 0.6 degrees) slope (indicated by the blue curve in Fig. 2). Taking into account that this slope has almost no effect on the dynamic loads between the wheel and the pavement [15], for simplification in the mathematical modeling of the pavement profile of a bridge crossing, the slope of the longitudinal profile is brought to 0 (indicated by the red curve in Fig. 2).

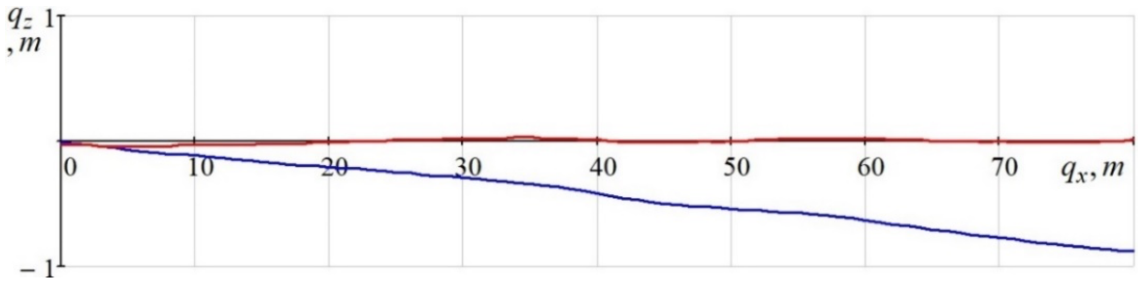

Fig. 2. Results of leveling the road surface of the bridge crossing

The second stage of experimental research involved video recording the nature of the truck's movement dynamics while crossing the bridge. Video recording was carried out simultaneously by six video cameras (Fig. 3a). The survey lines recorded the vertical fluctuations of the sprung and unsprung masses of the truck, which affect the dynamic loads in the contact of the car wheels with the road surface of the bridge crossing [15]. During the experimental studies, the real flow of motor vehicles crossing the bridge crossing was recorded. Among the transport flow, the MAN TGL 12.220 truck deserves special attention (Fig. 3b).

The truck MAN TGL 12.220 (Fig. 3a) belongs to the category of vehicles N2 – these vehicles are used to transport goods, and their total weight ranges from 3.5–12 t (according to Directive 2001/116/EC). According to statistics [16], the N2 category makes up 55% of all trucks registered in Ukraine from 2013 to 2023. At the same time, 63.3% of them have a total weight equal to 3.5 tons, 13.6% have a total weight between 3.5 t and 10 t, and 23.1% have a gross weight between 10 t and 12 t (inclusive). The latter are of the greatest interest for studying the dynamic load on the bridge crossing. Half of them are MAN TGL trucks. The total weight of the MAN TGL 12.220 truck (Fig. 3a), which is 12 tons, is at the upper limit of category N3. Therefore, the dynamics of the movement of the MAN TGL 12.220 truck through the bridge crossing were studied.

(a) (b)

Fig. 3. Places of installation of video cameras (a) to capture the nature of the movement of the MAN TGL 12.220 truck (b) while crossing the bridge crossing

The results of experimental studies were used to determine the initial and boundary conditions for calculations based on the mathematical model of the dynamics of the truck movement through the bridge. In addition, to confirm the adequacy of the proposed mathematical model, the obtained experimental data were used for comparison with the results of theoretical studies.

3. MATHEMATICAL MODEL OF THE DYNAMICS OF TRUCK MOVEMENT WHILE PASSING THE BRIDGE CROSSING

The analysis of the results of experimental studies shows that the movement of the truck across the bridge crossing is uniform and straight. The longitudinal profile of the road surface of the bridge along the sides of the wheels is assumed to be the same. To simplify the mathematical model of the dynamics of the truck's movement across the bridge, a half-car model was chosen (Fig. 4).

The calculation diagram at point *C* concentrates the sprung mass of the vehicle M_S, which takes into account the pitch moment of inertia J_Y. The position of the center of the car's unsprung masses is described by the longitudinal C_X and vertical C_Z coordinates, as well as the pitch angle α.

In this work, we use the indexing of parameters, where the lower index "*X*", "*Y*", or "*Z*" indicates the parameters belonging to the longitudinal, transverse, or vertical axis of the truck. The digital index "1" corresponds to the parameter belonging to the front axle of the truck, and "2" corresponds to the rear axle (Fig. 4).

For convenience, the equivalent unsprung mass of the vehicle m_S centered at point *S* is also used. The distance between the center of the unsprung masses and the equivalent unsprung mass of the front axle of the vehicle is denoted by the letter "*a*", and the rear axle is denoted by "*b*". The unsprung mass m_U is centered in the center of the wheel (at point *U*). The interconnection of these masses occurs through the elastic and dissipative suspension devices of the car wheels, which are modeled by the stiffness of the elastic suspension device k_S reduced to the car wheel and the coefficients of the shock absorber in the compression c_S^{com} and rebound stroke c_S^{reb}. The unsprung mass of the vehicle (point *U*) with the road surface of the bridge crossing (point *Q*) is connected through an elastic tire. The tire, in the plane of wheel rotation, is characterized by radial stiffness c_T and damping coefficient k_T.

In turn, the profile of the bridge pavement is described by the longitudinal Q_X and vertical Q_Z coordinates of the center of contact of the car wheel with the road surface (point *Q*), as well as the longitudinal angle of inclination of the road surface in contact with the wheel β [17].

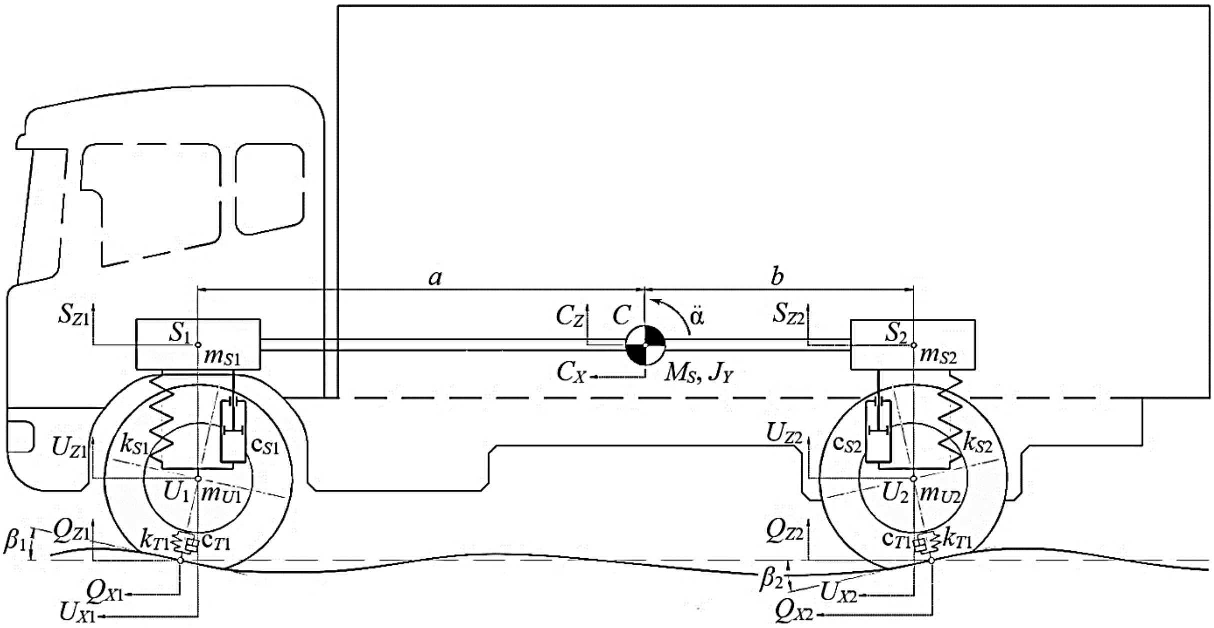

Fig. 4. Half-car model of the dynamics of the truck movement across the bridge crossing

Based on equations from [17, 18], a system of dynamics equations describing the vertical $\ddot{C}_Z$ and angular $\ddot{\alpha}$ accelerations of the center of masses of the truck, as well as the vertical accelerations of the unsprung masses of its front $\ddot{U}_{Z1}$ and rear $\ddot{U}_{Z2}$ axles, was developed:

$$\begin{cases} M_S \cdot \ddot{C}_Z = F_{S1} + F_{D1} + F_{S2} + F_{D2} - M_S \cdot g \\ J_Y \cdot \ddot{\alpha} = -a \cdot \left(F_{S1} + F_{D1} - m_{S1} \cdot g\right) + b \cdot \left(F_{S2} + F_{D2} - m_{S2} \cdot g\right) \\ m_{U1} \cdot \ddot{U}_{Z1} = R_{Z1} - F_{S1} - F_{D1} - m_{U1} \cdot g \\ m_{U2} \cdot \ddot{U}_{Z2} = R_{Z2} - F_{S2} - F_{D2} - m_{U2} \cdot g \end{cases}, \tag{1}$$

where F_S – the force from the deformation of the elastic suspension device reduced to the plane of rotation of the car wheel, N; F_D – the force of resistance of the suspension damper device reduced to the plane of rotation of the car wheel, N; g = 9.81 – acceleration of free fall, m/s^2; R_Z – vertical reaction of the bearing surface to the car wheel, N [17].

The forces from the deformation of the elastic suspension device F_S, the resistance of its damper device F_D, and the vertical reaction of the bearing surface to the car wheel R_Z, which are part of the system (1), are determined by the equations given in [17]. For these calculations, the vertical coordinates of the equivalent sprung masses reduced to the wheels of the front S_{Z1} and rear S_{Z2} axles of the vehicle, as well as the horizontal coordinates of the centers of contact of the wheels of the front Q_{X1} and rear Q_{X2} axles with the road (Fig. 4), can be written as follows:

$$S_{Z1} = C_Z - a \cdot \sin\alpha; \tag{2}$$

$$S_{Z2} = C_Z + b \cdot \sin\alpha; \tag{3}$$

$$Q_{X1} = C_X + a \cdot \cos\alpha + \left(\frac{S_{Z1} - U_{Z1}}{\cos\alpha}\right) \cdot \sin\alpha + r_{d1} \cdot \sin\beta_1; \tag{4}$$

$$Q_{X2} = C_X - b \cdot \cos\alpha + \left(\frac{S_{Z2} - U_{Z2}}{\cos\alpha}\right) \cdot \sin\alpha + r_{d2} \cdot \sin\beta_2, \tag{5}$$

where r_d is the dynamic radius of the vehicle wheel (determined by the equations given in [17]), m.

Given that this paper examines the uniform rectilinear motion of the truck, the current longitudinal coordinate of its center of unsprung mass C_X at the corresponding time t is determined taking into account its speed V_A. That is, $C_X = V_A \cdot t$.

The set of differential and algebraic equations used in mathematical modeling represents a system for the solution of which initial and boundary conditions are set, including the parameters of the bridge pavement and the truck. This approach was used in [18].

4. INITIAL AND BOUNDARY CONDITIONS FOR CALCULATIONS ACCORDING TO THE MATHEMATICAL MODEL OF TRUCK TRAFFIC DYNAMICS THROUGH THE BRIDGE CROSSING

The initial and boundary conditions for mathematical modeling are determined based on the results of data processing from experimental studies. The specified work can be divided into two parts: the first involves entering the geometric parameters of the road surface profile of the bridge crossing into the mathematical model, and the second involves the necessary design parameters and the nature of the truck's movement.

The analysis of the leveling results shows that the longitudinal profile of the road surface of the bridge crossing has harmonic profile irregularities (Fig. 5). Discrete empirical data were replaced by mathematical functions of the harmonic profile to eliminate gaps in the functions of the vertical coordinate Q_Z of the road surface profile of the bridge crossing and the current longitudinal angle β in contact with the wheels of the car (Fig. 4). In addition, the area of simulation of car movement before the beginning of overcoming harmonic irregularities of the road surface profile has been increased. For the convenience of analysis on graphical dependencies (Fig. 5), as well as further on in the text, the vertical lines of the beginning «*st*» and the end «*end*» of the bridge are displayed.

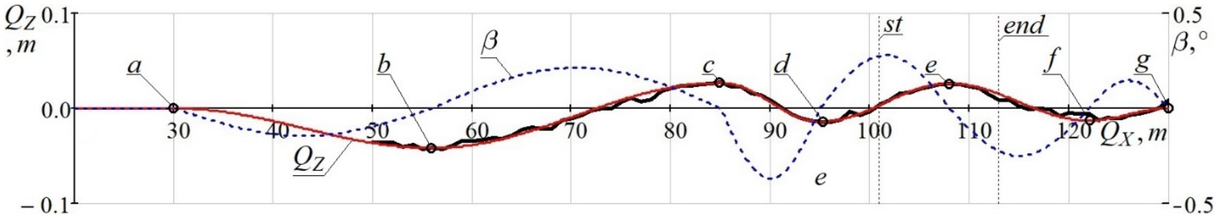

Fig. 5. Vertically enlarged (100 times) depiction of the longitudinal profile of the road surface of the bridge crossing, the dependence of its vertical coordinate Q_Z, and the longitudinal angle β on the longitudinal coordinate Q_X

For this, based on the analysis of the leveling results, the coordinates of the key points (*a*, *b*, *c*, *d*, *e*, *f*, *g*) of the longitudinal profile of the bridge transition (Fig. 6) were determined, which describe its harmonic profile:

$$a_X = 30;\quad b_X = 56;\quad c_X = 85;\quad d_X = 95;\quad e_X = 108;\quad f_X = 122;\quad g_X = 130;$$
$$a_Z = 0;\quad b_Z = -0.042;\quad c_Z = 0.027;\quad d_Z = -0.014;\quad e_Z = 0.026;\quad f_Z = -0.013;\quad g_Z = 0. \quad (6)$$

The functions of the vertical coordinate Q_{Zi} of the road surface of the bridge crossing and its longitudinal angle β_i in contact with the wheels of the i-th axle of the car, based on the equations [17], are written as follows:

$$Q_{Zi} = \begin{cases} a_Z + \dfrac{b_Z - a_Z}{2}\cdot\left[1-\cos\left(\dfrac{Q_{Xi}-a_X}{b_X-a_X}\cdot\pi\right)\right] & ,\text{if} \quad b_X \le Q_X < c_X \\ \dots & ,\text{if} \quad \dots ; \\ f_Z + \dfrac{g_Z - f_Z}{2}\cdot\left[1-\cos\left(\dfrac{Q_{Xi}-f_X}{g_X-f_X}\cdot\pi\right)\right] & ,\text{if} \quad f_X \le Q_X < g_X \\ 0 & - \quad \text{otherwise} \end{cases} \quad (7)$$

$$\beta_i = \begin{cases} \arctan\left[\dfrac{b_Z - a_Z}{b_X - a_X} \cdot \dfrac{\pi}{2} \cdot \sin\left(\dfrac{Q_{Xi} - a_X}{b_X - a_X} \cdot \pi\right)\right] & \text{, if} \quad a_X \le Q_{Xi} < b_X \\ \dots & \text{, if} \quad \dots \quad . \\ \arctan\left[\dfrac{g_Z - f_Z}{g_X - f_X} \cdot \dfrac{\pi}{2} \cdot \sin\left(\dfrac{Q_{Xi} - g_X}{f_X - g_X} \cdot \pi\right)\right] & \text{, if} \quad f_X \le Q_X < g_X \\ 0 & - \quad \text{otherwise} \end{cases} \tag{8}$$

To determine the modification and the parameters necessary for calculations of the MAN TGL 12.220 truck that crossed the bridge, we analyzed the stop frames from the video recording and compared them with the drawing [19] (Fig. 6). The parameters of the truck used in the mathematical model are given in Table 1.

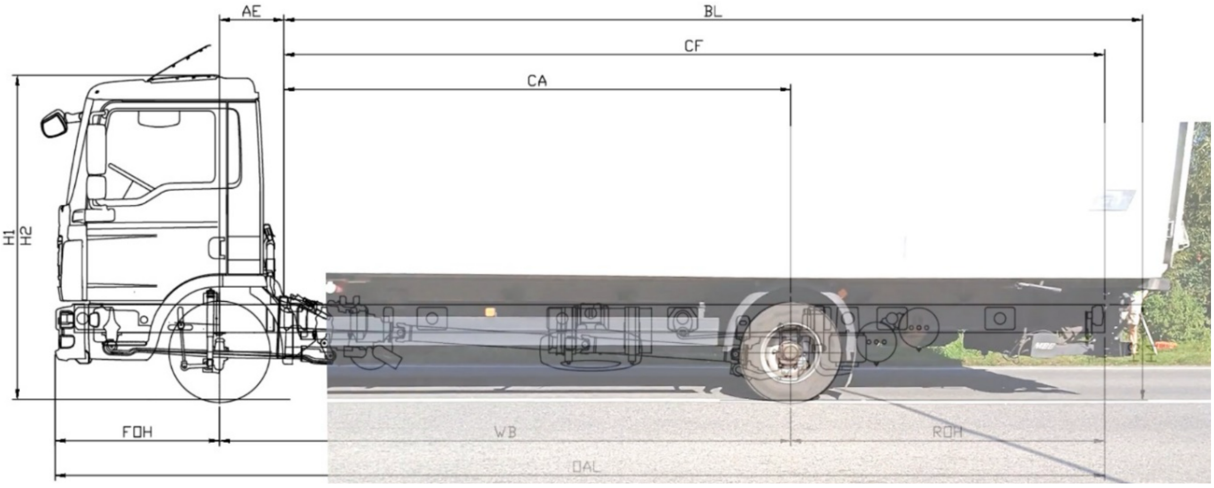

Fig. 6. Comparison of the stop frame from the video and the drawing of the MAN TGL 12.220

Table 1

Truck parameters used for mathematical modeling

№	Symbol	Parameter, unit	Value
1	M_S	Sprung mass of the truck, kg	11016
2	m_{S1}/m_{S2}	Equivalent sprung mass reduced to the front/rear axle, kg	3640/7376
3	m_{U1}/m_{U2}	Unsprung mass of the front/rear axle, kg	350/624
4	a/b	Distance from the center of the sprung masses to the front/rear axle, m	3.716/1.834
5	J_Y	Pitch moment of inertia, kg·m^2	$40 \cdot 10^3$
6	k_{S1}/k_{S2}	Front/rear suspension stiffness, N/m	$300 \cdot 10^3/700 \cdot 10^3$
7	$c_{S1}^{com} / c_{S1}^{reb}$	Front suspension damping coefficient (compression/rebound), N·s/m	$3 \cdot 10^3/15 \cdot 10^3$
8	$c_{S2}^{com} / c_{S2}^{reb}$	Rear suspension damping coefficient (compression/rebound), N·s/m	$4 \cdot 10^3/20 \cdot 10^3$
9	k_{T1}/k_{T2}	Radial stiffness of the front/rear tires, N/m	$1000 \cdot 10^3/2000 \cdot 10^3$
10	c_{T1}/c_{T2}	Front/rear tires damping coefficient, N·s/m	1500/3000

Parameters 1-4 (Table 1) were determined based on the reference information about the MAN TGL 12.220, and parameters 5-10 were determined by calculation and then compared with the parameters of similar trucks.

The approximate speed of the truck was determined by analyzing the video of the bridge crossing. Using the methodology for comparing theoretical and experimental data (discussed further in the text), the truck's speed V_A was refined to a value of 22.115 m/s.

5. THEORETICAL STUDIES OF TRUCK TRAFFIC DYNAMICS THROUGH THE BRIDGE CROSSING

Theoretical studies of the dynamics of the movement of a truck through a bridge crossing were carried out based on the proposed mathematical model and using the MathCad software. The calculation step during modeling is 0.001 s. The results of the calculations indicate the change in the vertical coordinates of the center of sprung masses C_Z of the truck, brought to its wheels of the front S_{Z1} and rear S_{Z2} axles of the equivalent sprung masses, the unsprung masses of its front U_{Z1} and rear U_{Z2} axles, as well as the change in the current value of the pitch angle α from the longitudinal coordinate of its center of sprung masses C_X (Fig. 7). Also, we determined the change in the vertical reactions of the road surface of the bridge crossing on the wheels of the front R_{Z1} and rear R_{Z2} axles of the truck from the longitudinal coordinate of its center of sprung masses C_X (Fig. 8).

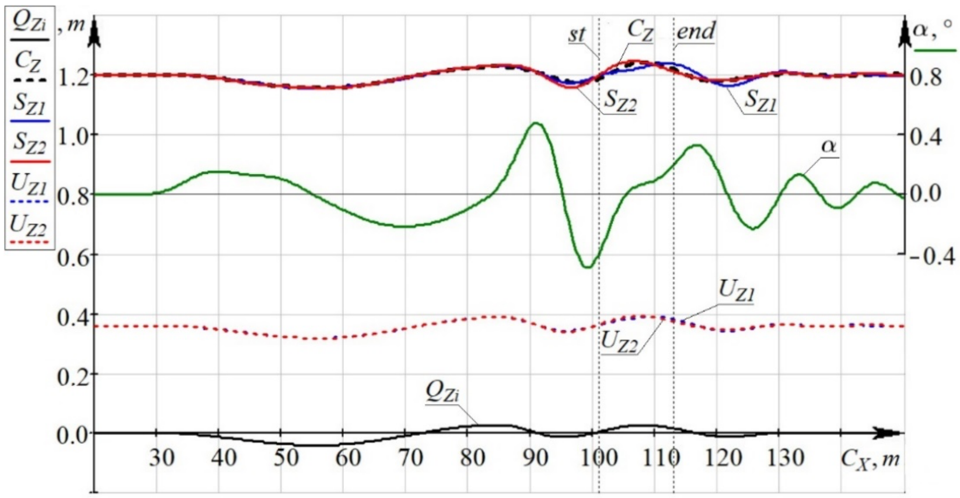

Fig. 7. Dependencies of the vertical coordinates of the center of sprung masses C_Z of a truck, brought to its front wheels S_{Z1} and rear S_{Z2} axes of equivalent sprung masses, unsprung masses U_{Z1} and U_{Z2}, as well as pitch angle α from the longitudinal coordinate of the center of sprung masses C_X

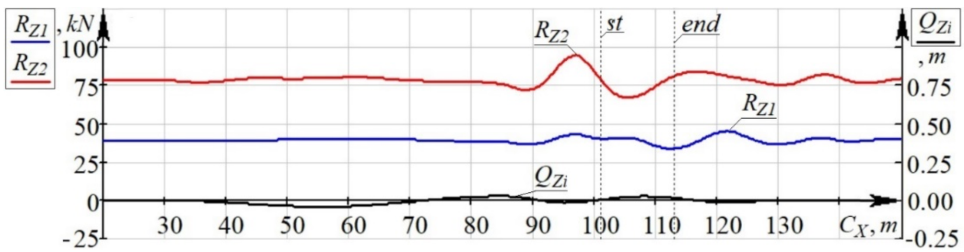

Fig. 8. Dependencies of the vertical reactions of the road surface of the bridge crossing on the wheels of the front R_{Z1} and rear R_{Z2} axles of the truck on the longitudinal coordinate of its center of sprung masses C_X

The graphs in Figs. 7 and 8 show that before the beginning of overcoming the harmonic profile of the road surface of the bridge crossing, the vertical coordinates of the center of the sprung masses C_Z of the truck, brought to its wheels of the front S_{Z1} and rear S_{Z2} axles of the equivalent sprung masses, unsprung the masses of its front U_{Z1} and rear U_{Z2} axes, as well as the current value of the pitch angle α are constant and correspond to their static values. After the harmonic profile (in the area of 30 m) of the road surface of the bridge crossing begins to be overcome, a wave-like change of all the indicated parameters of the truck movement begins. This is explained by the fact that, starting from 30 m, there is a change in the parameters of the support surface of the bridge crossing, which is accompanied by a change in the vertical reactions in contact with the wheels of the car. This leads to fluctuations in the sprung and unsprung masses of the truck.

It is worth noting that in the area of the beginning of the approach to the bridge (in the area of overcoming 90 m), there is a short-term decrease in the vertical reactions of the support surface on the wheels of the truck. This is explained by the decrease in the vertical coordinate of the road surface of the bridge crossing Q_Z. At the same time, already in the region of overcoming 95 m, the vertical reactions on the wheels reach their local maxima: for the front axle R_{Z1}, this is almost 43 kN; for the rear axle R_{Z2}, it is 94 kN (Fig. 8). This is explained by an increase in the vertical coordinate of the road surface of the bridge crossing Q_Z, while the equivalent sprung masses of the truck brought to the front S_{Z1} and rear S_{Z2} axles continue to move down by compared to the static load inertia (Fig. 7). However, this is accompanied by a slight increase in the dynamic load: for the front axle, this is less than 10%, and for the rear axle, it is 20%.

These results are correlated with the results of the DIVINE study [14], which noted that in the case of a smooth bridge profile and approaches to it on bridges of medium length, the influence of the vehicle suspension on the dynamic load on the wheels and the response value of the bridge elements was not very significant.

6. CONFIRMATION OF THE ADEQUACY OF THE MATHEMATICAL MODEL

The method of analysis of experimental and theoretical studies of the dynamics of car movement, proposed in the paper [18], was used to confirm the adequacy of the proposed mathematical model. The peculiarity of the technique is that a semi-transparent visualization image (hereinafter referred to as "animation") of the movement of a truck is "imposed" on the materials from the video cameras. The animations were created using the MathCad software package. The current position of the characteristic points of the truck (coordinates of the points on the three-dimensional graphic field) was determined based on the results of calculations on the proposed mathematical model. After achieving the coincidence of the filming lines on video materials and in animations (including taking into account the scale and perspective), the results of experimental and theoretical studies were synchronized in time. Saving the obtained result in the form of a screenshot makes it possible to build a series of still frames (Fig. 9) or create a video file for a visual comparison of the level of coincidence of the results of theoretical studies with experimental ones and to evaluate the reliability of theoretical information obtained on the proposed mathematical model.

The results (Fig. 9) show a high level of coincidence of the nature of the vertical dynamics of the MAN TGL 12.220 truck while crossing the bridge crossing – in particular, the vertical oscillations of the sprung and unsprung masses of the truck, as well as changes in the pitch angle. This highlights the adequacy of the proposed mathematical model and the reliability of the theoretical information obtained on it, in particular, the dynamic loads acting from the wheels of the truck on the road surface of the bridge crossing. This is explained by the fact that vertical fluctuations of the sprung and unsprung masses of the truck, as well as changes in the pitch angle, are caused by vertical reactions acting during the contact of the wheels with the road surface of the bridge crossing.

Based on the results of experimental research, this approach made it possible to prove the adequacy of the proposed mathematical model of the dynamics of truck movement through a bridge crossing. This makes it possible to conduct theoretical studies of dynamic loads acting between the wheels of a truck and the bridge crossing with a road surface defect according to the proposed mathematical model.

7. THEORETICAL STUDIES OF TRUCK MOTION DYNAMICS WHEN CROSSING THE BRIDGE CROSSING WITH A ROAD SURFACE DEFECT

According to the proposed mathematical model, theoretical studies similar to the previous ones were conducted. The only difference is that the road surface of the bridge crossing, in the area of the approach to the bridge, in the path of the wheels on both sides, is supplemented with a pothole with a depth of 0.075 m and a length of 1 m [17].

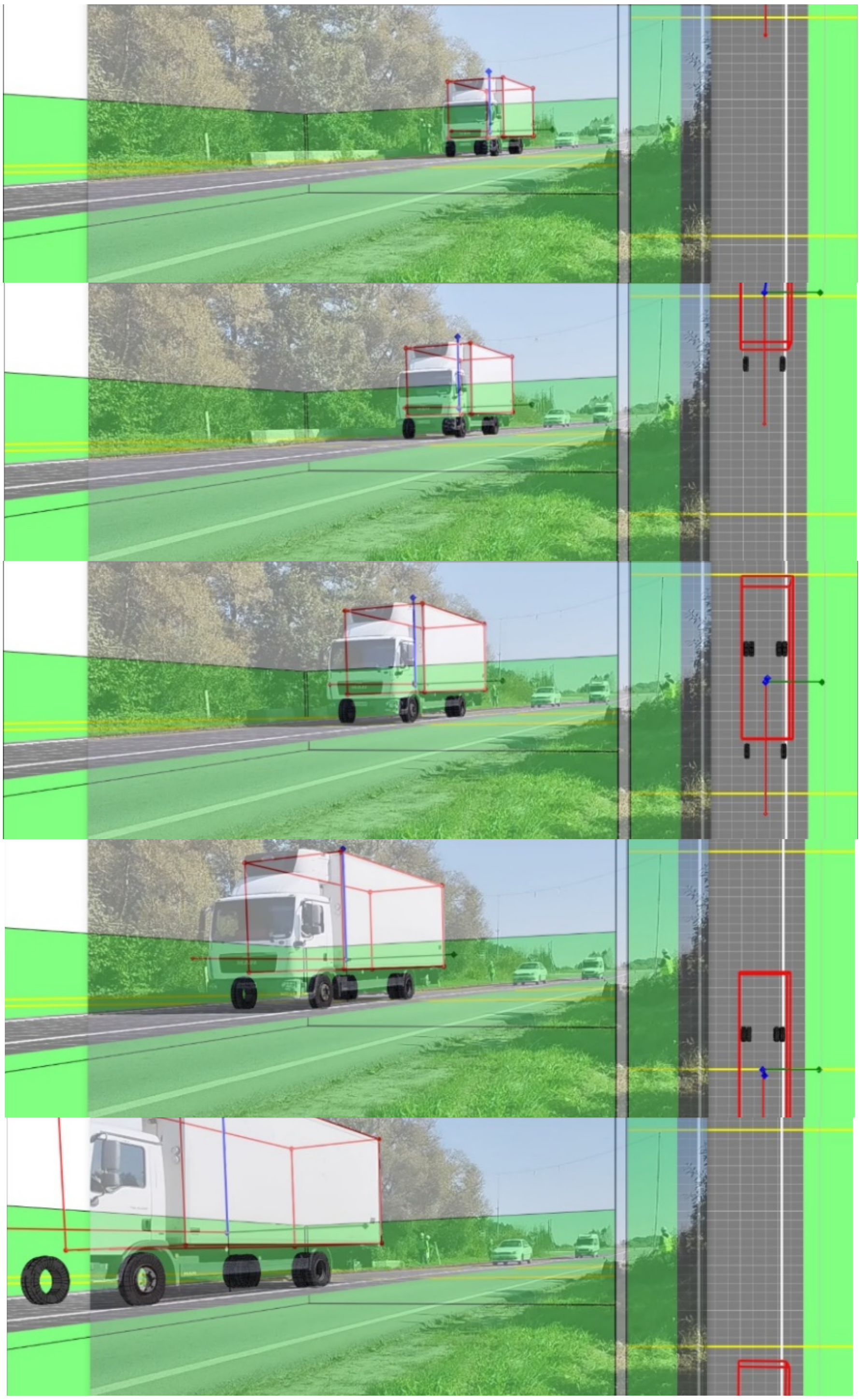

Fig. 9. Comparison of the results of theoretical studies with experimental ones

The calculations determined the change in the vertical reactions of the road surface of the bridge on the wheels of the front R_{Z1} and rear R_{Z2} axles of the truck from the longitudinal coordinate of its center of sprung masses C_X (Fig. 10). For convenience of analysis of dynamic loads in the region of overcoming potholes and bridges, the obtained results are displayed on a separate graphic field (Fig. 11).

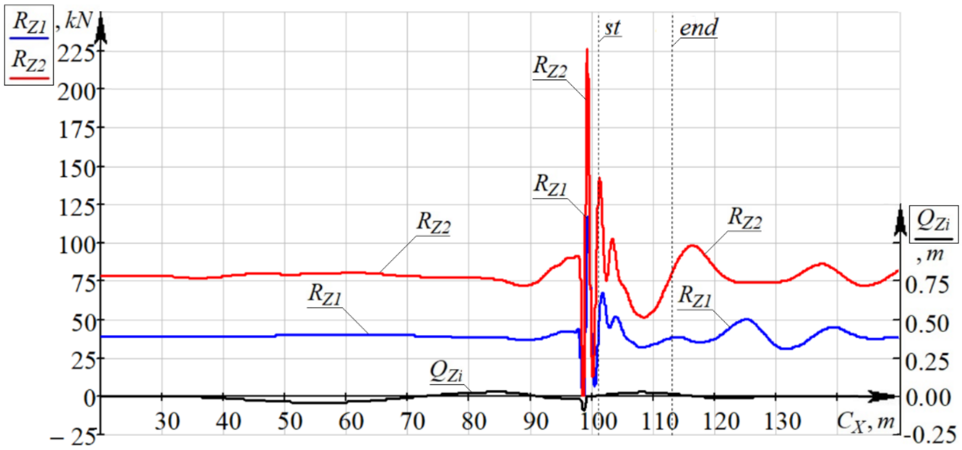

Fig. 10. Dependencies of the vertical reactions of the road surface of the bridge crossing on the wheels of the front R_{Z1} and rear R_{Z2} axles of the truck on the longitudinal coordinate of its center of sprung masses C_X

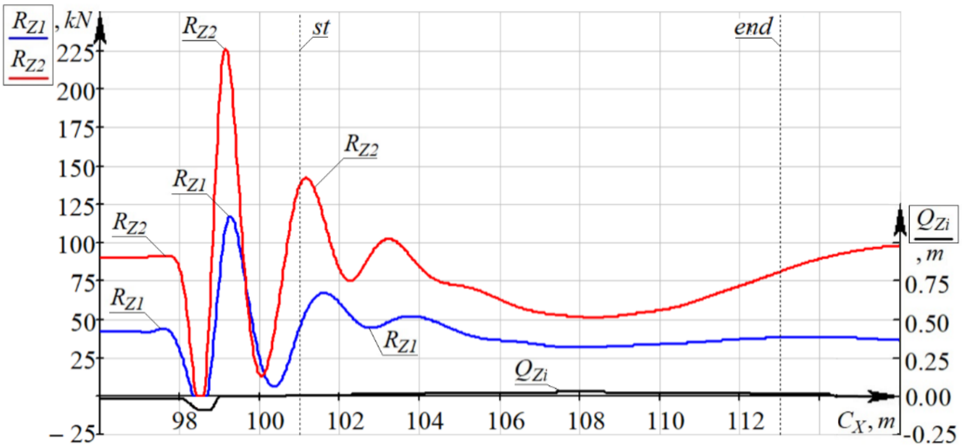

Fig. 11. Dependencies of the vertical reactions of the road surface of the bridge crossing on the wheels of the front R_{Z1} and rear R_{Z2} axles of the truck on the longitudinal coordinate of its center of sprung masses C_X in the area of overcoming the pothole and the bridge

Fig. 10 shows that before overcoming the harmonic profile of the road surface of the bridge crossing, the vertical reactions on the wheels are constant and correspond to static values. In the area of the beginning of the approach to the bridge (the area of overcoming 90 m), a short-term decrease in the vertical reactions of the support surface on the wheels of the truck was observed. This is explained by the decrease in the vertical coordinate of the road surface of the bridge crossing Q_Z. In the area of overcoming 95 m, the vertical reactions on the wheels reached their local maxima: for the front axle R_{Z1}, this is almost 43 kN; for the rear axle R_{Z2}, it is 91 kN (Fig. 10).

After the start of overcoming the pothole (the area of 98 m) (Fig. 11), there is a rapid decrease to zero of the vertical reactions of the road surface on the wheels of the truck (detachment of the wheels from the supporting surface). At the same time, after about a meter of the traveled path (at the end of the pothole), there is a rapid increase in vertical reactions to their maximum values: for the wheels of the front axle R_{Z1}, it is almost 117 kN; for the rear axle R_{Z2}, it is 226 kN. Almost immediately after that, the vertical reactions decrease again: for the wheels of the front axle R_{Z1}, the decrease is to 117 kN; for the rear axle R_{Z2}, it is 13 kN.

In the area of overcoming the beginning of the bridge (Fig. 11), there is a repeated rapid increase in vertical reactions: for the wheels of the front axle R_{Z1}, this increase is almost 77 kN; for the rear axle R_{Z2}, it is almost 142 kN.

After crossing the middle of the bridge (the area of 108 m) (Fig. 11), a decrease in vertical reactions is observed: for the wheels of the front axle R_{Z1}, this decrease is 32 kN; for the rear axle R_{Z2}, it is 51 kN. Further, the vertical responses gradually stabilize (Fig. 10) in the region of static values (not shown on graphical dependencies).

The calculations reveal the maximum values of dynamic loads relative to static ones: for the front axle of the truck, this value increased by 198%; for the rear axle, it increased by 188%.

The calculations were performed on the proposed mathematical model, the adequacy of which was confirmed by the comparison method based on the results of experimental studies. This confirms the reliability of the theoretical information obtained in this work, specifically regarding the dynamic load acting between the wheels of the truck and the overpass with a defect in the road surface.

8. CONCLUSIONS

1. There are few approaches to the full-scale study of the dynamic load from truck wheels on the pavement of a bridge crossing. A comprehensive study of the dynamics of truck movement over a bridge crossing, including those with road surface defects, was carried out. This approach involved experimental and theoretical studies, followed by a comparison of the results to confirm the adequacy of the proposed mathematical model.
2. During the experimental studies, the profile of the road surface of the bridge crossing was leveled with a step of 1 m, and the nature of the truck movement was recorded. Video recording was carried out simultaneously by six video cameras. The recording lines captured vertical oscillations of the truck's sprung and unsprung masses, which affected the dynamic loads in the contact of the wheels with the bridge pavement. The objects of the study were a bridge crossing over the Rakuv River on the international public road M-11 "Lviv – Shehyni" (a single-span bridge with a length of 12 m) and a MAN TGL 12.220 truck.
3. A mathematical model of the dynamics of the truck movement across the bridge crossing was proposed. A system of dynamics equations describing the vertical and angular accelerations of the centroid of the truck's sprung masses, as well as the vertical accelerations of the unsprung masses of its front and rear axles, was developed. Initial and boundary conditions for calculations using the mathematical model were formulated based on experimental studies. The results of theoretical studies show that the dynamic loads from the truck wheels do not exceed 20% when crossing the bridge with a smooth undulating harmonic profile.
4. To confirm the adequacy of the proposed mathematical model, a comparative analysis of the results of theoretical and experimental studies was carried out. The high level of coincidence of the nature of the vertical dynamics of the MAN TGL 12.220 truck movement while crossing the bridge – in particular, vertical oscillations of the truck's sprung and unsprung masses, as well as changes in the pitch angle – indicates the adequacy of the proposed mathematical model and the reliability of the theoretical information obtained from it.
5. Theoretical studies of the dynamic loads acting between the wheels of the truck and the bridge crossing with a road surface defect were carried out using the proposed mathematical model. The defect is a pothole in the path of the wheels on both sides with a depth of 0.075 m and a length of 1 m. After the pothole begins to be overcome, the wheels detached from the bearing surface. The resumption of wheel contact was accompanied by a rapid increase in vertical reactions to their maximum values: for the front axle wheels, this value was almost 117 kN; for the rear axle, it was 226 kN. Almost immediately after that, the vertical reactions decreased again: for the front axle wheels, the decrease was to 117 kN; for the rear axle, it was to 13 kN. In the area of overcoming the beginning of the bridge, a repeated rapid increase in vertical reactions was observed: for the wheels of the front axle R_{Z1}, this was almost 77 kN; for the rear axle R_{Z2}, it was almost 142 kN. The calculations show the maximum values of dynamic loads relative to static loads: for the front axle of the truck, the load increased by 198%; for the rear axle, it increased by 188%. The calculations were carried out based on the proposed mathematical model, the adequacy of which was confirmed by a comparison with the results of experimental studies. This confirms the reliability of the theoretical

information obtained in this work and the effectiveness of a comprehensive study of the dynamics of the truck's movement across the bridge crossing, which makes it possible to determine the dynamic load acting between its wheels and the road surface of the bridge, including the presence of a pothole.

References

1. Nowak A.S. Live load model for highway bridges. *Structural Safety*. 1993. Vol. 13. No. 1-2. P. 53-66.
2. O'Connor, A. & O'Brien, E.J. Traffic load modelling and factors influencing the accuracy of predicted extremes. *Canadian Journal of Civil Engineering*. 2005. Vol. 32. No. 1. P. 270-278.
3. Obrien, E.J. & Leahy, C. & Enright, B. & Caprani, C.C. Validation of scenario modelling for bridge loading. *The Baltic Journal of Road and Bridge Engineering*. 2016. Vol. 11. No. 3. P. 233-241.
4. O'Brien, E.J. & Cantero, D. & Enright, B. & González, A. Characteristic dynamic increment for extreme traffic loading events on short and medium span highway bridges. *Engineering Structures*. 2010. Vol. 32. No. 12. P. 3827-3835.
5. Cantero, D. & González, A. & O'Brien, E.J. Comparison of bridge dynamic amplifications due to articulated 5-axle trucks and large cranes. *The Baltic Journal of Road and Bridge Engineering*. 2011. Vol. 6. No. 1. P. 39-47.
6. González, A. & O'Brien, E.J. & Cantero, D. & Li, Y. & Dowling, J. & Žnidarič, A. Critical speed for the dynamics of truck events on bridges with a smooth road surface. *Journal of Sound and Vibration.* 2010. Vol. 329. No. 11. P. 2127-2146.
7. Nowak, A.S & Lutomirska, M. & Sheikh Ibrahim, F.I. The development of live load for long span bridges. *Bridge Structures*. 2010. Vol. 6. No. 1, 2. P. 73-79.
8. Micu, E.A. & O'Brien, E.J. & Malekjafarian, A. & Quilligan, M. Estimation of extreme load effects on long-span bridges using traffic image data. *The Baltic Journal of Road and Bridge Engineering*. 2018. Vol. 13. No. 4. P. 429-446.
9. Lipari, A. & Caprani, C.C. & O'Brien, E.J. A methodology for calculating congested traffic characteristic loading on long-span bridges using site-specific data. *Computers & Structures.* 2017. Vol. 190. P. 1-12.
10. Yang, Y.B. & Jong-Dar Yau. Vehicle-bridge interaction element for dynamic analysis. *Journal of Structural Engineering.* 1997. Vol. 123. No 11. P. 1512-1518.
11. Jacob, B. & O'Brien, E.J. & Newton, W. Assessment of the accuracy and classification of weigh-in-motion systems. Part 2: European specification. *International Journal of Heavy Vehicle Systems*. 2004. Vol. 7. No. 2/3. P. 153-168.
12. Haider, S.W. & Masud, M.M. & Selezneva, O. & Wolf, D.J. Assessment of factors affecting measurement accuracy for high-quality weigh-in-motion sites in the long-term pavement performance database. *Transportation Research Record Journal of the Transportation Research Board*. 2020. Vol. 2674. No. 10. P. 269-284.
13. Melcer, J. A Vehicle – bridge interaction. *Communications – Scientific letters of the University of Zilina*. 2007. Vol. 9. No. 3. P. 5-10.
14. Tseng, E. & Germanchev, A. *Dynamic Load Effects of Heavy Vehicles on Pavement Performance – Stage 1*. Western Australian Road Research and Innovation Program. 2018. 68 p.
15. Разбойніков, О.О. & Давиденко, О.О. & Козарчук, І.А. & Клочан, А.Є. Вплив якісного стану дорожнього покриву мостів на характер руху автотранспортних засобів. *Автомобільні дороги і дорожнє будівництво*. 2023. Vol. 114 No 1. P. 88-97. [In Ukrainian: Razboinikov, O.O. & Davydenko, O.O. & Kozarchuk, I.A. & Klochan, A.E. The influence of the quality condition of the road surface of bridges on the character of vehicle traffic. *Automobile roads and road construction*].
16. Відомості про транспортні засоби та їх власників. Available at: https://data.gov.ua/dataset/06779371-308f-42d7-895e-5a39833375f0 [In Ukrainian: Information about vehicles and their owners].

17. Slavinska, O. & Bubela, A. & Razboinikov, O. & Davydenko, O. & Ivanushko, O. & Kozarchuk, I. Assessment of the dynamic impact of a truck on the bridge pavement based on the proposed mathematical model of vehicle movement. *Nanotechnology Perceptions*. 2024. Vol. 20. No. S1. P. 231-251.
18. Разбойніков, О. О. *Поліпшення курсової стійкості легкового автомобіля при русі по нерівній дорозі*. PhD thesis. Київ: НТУ. 2021. 214 p. [In Ukrainian: Razboinikov, O. O. *Improving the directional stability of a passenger car when driving on an uneven road*. PhD thesis. Kyiv: NTU].
19. TGL 4x2 Chassis C, L and DK Cab. Available at: https://resource.digitaldealer.com.au/pdf/91237032660460e81a468a667901234.pdf.

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