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DEVISING AN APPROACH TO ASSESSING THE DURABILITY OF BUS BODY ON A FRAME CHASSIS

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The object of this study is the processes and permissible limits of aging of bus bodies on the frame chassis during operation.

As a result of research by simulation method, the durability of the bus on the frame chassis, was determined, which is in the range from 5 to 11 years depending on the operating conditions. The study took into account the following factors: passenger occupancy, microprofile of the road, bus speed, corrosion. The durability of the bus depends primarily on the durability of the frame and body frame. Since the frame is made of alloy steels and heat-treated, it is not repaired but replaced with a new one when cracks in the frame are formed.

When determining the durability of the bus on the frame chassis, it was found that the frame has 1.5–1.8 times greater durability than the body frame itself. This is because the frame is made of alloyed materials and has an open structure. The body frame has closed cavities, which provoke the development of corrosion with the accumulation of moisture in them.

A feature of the results is that previous studies considered buses only with a load-bearing body structure.

The issue of durability of bodies on the frame chassis has been considered. As experience shows, the durability of bus bodies on a frame chassis depends on many operational factors. For operating organizations and manufacturing plants, it is important to provide for the durability of the bus depending on the operating conditions.

The results of this study will allow operating organizations to provide for scheduled repairs, as well as take measures to increase the service life of buses during operation. For manufacturing plants, the findings will make it possible to apply rational technologies and materials to form the service life of the bus body

Keywords: bus body durability, frame chassis, simulation, body corrosion, fatigue destruction

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1. Introduction

In design practice, it is accepted that buses are rationally manufactured on the assembly base of truck chassis, the characteristics of which are as close as possible to the operating conditions of buses [1]. That is, buses are made on the basis of existing machine assembly kits. The larger the unification of a designed bus with a machine assembly kit of the freight chassis, the simpler the manufacturing technology. Therefore, buses are equipped with the maximum number of units from trucks: engine, transmission, front, rear axle, etc. And all these units are attached to the frame of the truck. Accordingly, the frame is borrowed from the truck. This is how the bus on the frame chassis is designed. Despite a number of shortcomings (the larger cost of a machine assembly kit, an increased center of mass, the impossibility of restoring a hardened frame made of alloyed materials), buses on the frame chassis have become very popular when transporting passengers. A feature of the design of such buses is the use of the installed body frame on the frame as a superstructure. As a result of the operation of such a bus, the durability of a hardened open-type frame made of alloy steel and a frame of the body of a welded structure made of steel pipes of a closed type will inevitably differ.

With the development of computer modeling applications [2], the calculation of the durability of bus bodies became possible [1]. In particular, the software package Matlab Simulink (USA) [2] makes it possible to generate perturbations from the microprofile of the road through tyres and suspension transmitted to the bus body. This became possible when combined with the speed of the bus, passenger loading, corrosion, etc. Such applications make it possible to bring computer modeling as close as possible to the realities of operation.

The results of such studies are necessary in practice because operating organizations need to know the durability of the bus body on the frame chassis. Such research results will allow operating organizations to rationally and timely carry out restoration repairs of bus bodies. Also, such results will provide for the feasibility of carrying out restoration repairs depending on the service life. For manufacturing plants, information on the resource of the bus body on the frame chassis will make it possible to change the structure and use materials at the design stage. A rational option would be to equalize the durability of the frame and the frame of the bus body. Such structural solutions will make it possible to form the resource of the bus at the stage of design and production.

Thus, taking into account modern methods of computer simulation [2] and the feasibility of conducting research, it becomes possible to calculate the durability of the bus on the frame chassis.

2. Literature review and problem statement

In [1], the procedure was described and the durability of the bus body of the load-bearing structure was determined. However, in paper [1], no calculation of the durability of the bus on the frame chassis was carried out. Part of the methodology of the cited work [1] is suitable for determining the durability of the bus body on the frame chassis since the main force structure of the body, described in [1], is concentrated in the lower part of the body but needs to be improved taking into account the features of the frame operation [1]. In [3], simulation of the bus on the frame chassis was carried out when tipping to the side, which made it possible to determine the compliance of the bus with Rules No. 66 of the UNECE [4]. In [3], the bus was inspected during operation, where the deformation of the body frame racks was determined. However, the degradation of the frame material in work [3] was not taken into account and the comparative calculation of the bus frame and frame was not carried out. In [5], the authors report a procedure of simulation for the compliance of the bus with Rules No. 66 of UNECE at the stage of certification before mass production. However, they do not take into account the aging of the body material and the bus frame during operation. In [6], the durability of polyurethane adhesive joints for aluminum assembly of bus structures is assessed. The use of such materials will increase the durability of bus bodies, with an increase in the cost of production. In paper [6], there is no information on determining the durability of buses on the frame chassis. In [7], the determination of the fatigue life of the structure of a low-floor bus during normal operation and with accelerated testing was carried out. In the paper, no study of the bus on the frame chassis was carried out since low-floor buses have a load-bearing and frameless body structure. In [8], the practical principles for assessing the fatigue resource of buses and trolleybuses are given. In [8], it is proposed to conduct laboratory tests of welded elements only of the load-bearing body frame. This approach [8] could subsequently be used in full-scale tests of the bus frame for durability. Paper [9] describes the methodology of accelerated testing of buses only with a load-bearing body on roads with a special coating. This procedure [9] involves the implementation of a number of full-scale experiments, which is quite expensive. The methodology presented in [9] is not fully suitable for determining the resource of the bus on the frame chassis since it provides for the study of low-floor buses of load-bearing design. The main force structure of such a body [9] is concentrated in its upper part (reinforced roof). For buses on the frame chassis, the main force loads are perceived by the frame in the lower part of the bus body, which should be emphasized in further studies.

As a result of the review of literary data [1, 6–9] it was found that there are several options for determining the durability of bus bodies with a load-bearing structure. However, no studies have been found to determine the durability of bus bodies on the frame chassis. Therefore, it suggests that it is advisable to conduct a study on assessing the durability of the bus body on the frame chassis.

3. The aim and objectives of the study

The aim of this study is to develop an approach to assessing the durability of the bus body on the frame chassis. This will make it possible to assess the durability of the bus body not only with a load-bearing structure (a solid body of the «monocoque» type) but also of a bus whose body is built up on the frame chassis, making changes to the body structure at the design stage and influence durability even before operation.

To accomplish the aim, the following tasks have been set:

– to improve the methodology reported in [1] to determine the durability of the bus body with a load-bearing structure for the possibility of conducting research of buses on the frame chassis;

– to assess the durability of the bus body on the frame chassis using computer simulation.

4. The study materials and methods

The object of our study is the processes and permissible limits of aging of bus bodies on the frame chassis during operation.

The main hypothesis of the study assumes that during the operation of the bus, the mechanical characteristics of its body on the frame chassis constantly deteriorate. Such a deterioration is associated with the accumulation of sites of fatigue destruction. Fatigue destruction is provoked by the impact of irregularities in the microprofile of the road surface on the body, combined with passenger loading, traffic speed, and corrosion.

The body of the bus, as a dynamic system, in addition to disturbing and potential forces, is also exposed to resistance forces realized on the basis of the Lagrange equation of the second order [10]:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_k}\right)-\frac{\partial T}{\partial q_k}=-\frac{\partial P}{\partial q_k}-\frac{\partial F}{\partial \dot{q}_k}, \tag{1}$$

where $k=1, 2, ..., n$; n – the number of degrees of freedom of a dynamical system; T – kinetic energy of the system; P – potential energy of the system; F – scattering function (Rayleigh function); q_k is the k-th generalized coordinate.

In a previous model [1, 10], the longitudinal-angular vibrations Θ of the body were taken into account, which was necessary in determining the durability of the body with a load-bearing structure. In addition, the model from [1, 10] provided for the calculation of the bus body with different loads by passengers, which led to a shift in the center of gravity of the bus. That caused some difficulties in accurately determining the center of gravity of the bus when loading the bus above the norm (82 passengers instead of the maximum allowable 52 passengers) [1]. In addition, the rear suspension of the bus with a body with a load-bearing structure [1] consists of sheet and pneumatic springs, which is required to compensate for the loading of the bus with a long rear overhang. For this type of body [1, 10] there was a need to take into account the longitudinal-angular vibrations of the bus. Unlike a bus with a load-bearing structure [1, 10], the bus with a frame structure has a larger rigidity and all suspensions made of sheet springs. In addition, to determine the durability of the body on the frame chassis and compare with the durability of its frame, it is enough to predict durability with the maximum allowable load (40 passengers – without overload) at an average speed of 40 km/h. Given the above, there is no need to take into account longitudinal-angular vibrations when calculating the durability of the body on the frame chassis, which will make it possible to reduce the number of degrees of freedom and achieve more stable indicators of the body relative to the durability of the frame.

The proposed dynamic system has three degrees of freedom. Its position in space is determined by three generalized coordinates $q_1 = x$, $q_2 = y$, $q_3 = z$.

Vertical oscillations of sprung masses of the bus of the frame structure M_S and unsprung masses m_1 and m_2 relative to static equilibrium without taking into account longitudinal-angular oscillations are considered:

$$\left.\begin{aligned} T &= \frac{1}{2}\left(M_S\cdot\dot{z}^2 + m_1\cdot\dot{x}_1^2 + m_2\cdot\dot{x}_2^2\right);\\ P &= \frac{1}{2}\begin{bmatrix} c_{S1}\left(x_1 - z\right)^2 + c_{S2}\left(x_2 - z\right)^2 + \\ +c_{W1}\left(y_1 - x_1\right)^2 + c_{W2}\left(y_2 - x_2\right)^2 \end{bmatrix};\\ F &= \frac{1}{2}\begin{bmatrix} k_{a1}\left(\dot{x}_1 - \dot{z}\right)^2 + k_{a2}\left(\dot{x}_2 - \dot{z}\right)^2 + \\ +k_{W1}\left(\dot{y}_1 - \dot{x}_1\right)^2 + k_{W2}\left(\dot{y}_2 - \dot{x}_2\right)^2 \end{bmatrix}, \end{aligned}\right\} \qquad (2)$$

where x, y, z – height of irregularities of the microprofile of the road, coordinates of movement in the vertical plane of unsprung and sprung masses; k_{a1}, k_{a2}, c_{S1}, c_{S2} – coefficients of damping and stiffness of the elastic elements of the front and rear suspensions; k_{W1}, k_{W2}, c_{W1}, c_{W2} – coefficients of damping and stiffness of the wheels of the front and rear axles; M_S – sprung mass of the bus; m_1, m_2 – unsprung masses of the bus, respectively, front and rear axles.

Fig. 1 shows the scheme according to which the research was conducted.

Differentiating equation (2) yields the following:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{x}_k}\right) = \frac{1}{2}\left[2m_1\cdot\ddot{x}_1 + 2m_2\cdot\ddot{x}_2\right] = m_1\cdot\ddot{x}_1 + m_2\cdot\ddot{x}_2, \qquad (3)$$

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{z}}\right) = \frac{1}{2}M_S\cdot 2\ddot{z} = M_S\cdot\ddot{z}, \qquad (4)$$

$$\frac{\partial T}{\partial x_1} = \frac{\partial T}{\partial x_2} = \frac{\partial T}{\partial z} = 0, \qquad (5)$$

$$\begin{aligned} \frac{\partial P}{\partial x_k} &= \frac{1}{2}\begin{bmatrix} 2c_{S1}\left(x_1 - z\right) + 2c_{S2}\left(x_2 - z\right) - \\ -2c_{W1}\left(y_1 - x_1\right) - 2c_{W2}\left(y_2 - x_2\right) \end{bmatrix} = \\ &= c_{S1}\left(x_1 - z\right) + c_{S2}\left(x_2 - z\right) - \\ &-c_{W1}\left(y_1 - x_1\right) - c_{W2}\left(y_2 - x_2\right), \end{aligned} \qquad (6)$$

$$\begin{aligned} \frac{\partial P}{\partial z} &= \frac{1}{2}\left[-2c_{S1}\left(x_1 - z\right) - 2c_{S2}\left(x_2 - z\right)\right] = \\ &= -c_{S1}\left(x_1 - z\right) - c_{S2}\left(x_2 - z\right), \end{aligned} \qquad (7)$$

$$\begin{aligned} \frac{\partial F}{\partial \dot{x}_k} &= \frac{1}{2}\begin{bmatrix} 2k_{a1}\left(\dot{x}_1 - \dot{z}\right) + 2k_{a2}\left(\dot{x}_2 - \dot{z}\right) - \\ -2k_{W1}\left(\dot{y}_1 - \dot{x}_1\right) - 2k_{W2}\left(\dot{y}_2 - \dot{x}_2\right) \end{bmatrix} = \\ &= k_{a1}\left(\dot{x}_1 - \dot{z}\right) + k_{a2}\left(\dot{x}_2 - \dot{z}\right) - \\ &-k_{W1}\left(\dot{y}_1 - \dot{x}_1\right) - k_{W2}\left(\dot{y}_2 - \dot{x}_2\right), \end{aligned} \qquad (8)$$

$$\begin{aligned} \frac{\partial F}{\partial \dot{z}} &= \frac{1}{2}\left[-2k_{a1}\left(\dot{x}_1 - \dot{z}\right) - 2k_{a2}\left(\dot{x}_2 - \dot{z}\right)\right] = \\ &= -k_{a1}\left(\dot{x}_1 - \dot{z}\right) - k_{a2}\left(\dot{x}_2 - \dot{z}\right). \end{aligned} \qquad (9)$$

The obtained values of derivatives (3) to (9) are substituted into equations (1):

$$\left.\begin{aligned} &M_S\cdot\ddot{z} - 0 = -\left[-c_{S1}\left(x_1 - z\right) - c_{S2}\left(x_2 - z\right)\right] - \\ &-\left[-k_{a1}\left(\dot{x}_1 - \dot{z}\right) - k_{a2}\left(\dot{x}_2 - \dot{z}\right)\right];\\ &m_1\cdot\ddot{x}_1 - 0 = -\left[c_{S1}\left(x_1 - z\right) - c_{W1}\left(y_1 - x_1\right)\right] - \\ &-\left[k_{a1}\left(\dot{x}_1 - \dot{z}\right) - k_{W1}\left(\dot{y}_1 - \dot{x}_1\right)\right];\\ &m_2\cdot\ddot{x}_2 - 0 = -\left[c_{S2}\left(x_2 - z\right) - c_{W2}\left(y_2 - x_2\right)\right] - \\ &-\left[k_{a2}\left(\dot{x}_2 - \dot{z}\right) - k_{W2}\left(\dot{y}_2 - \dot{x}_2\right)\right]. \end{aligned}\right\} \qquad (10)$$

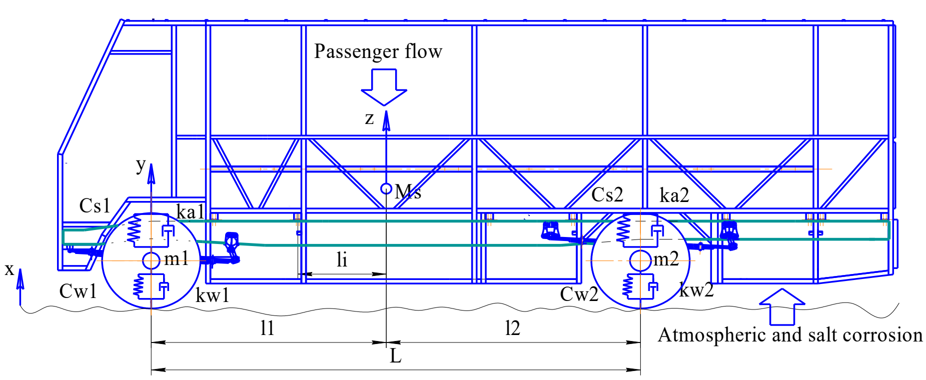

Fig. 1. Scheme for assessing the durability of the bus body on the frame chassis

The result is:

$$\left.\begin{aligned}
&M_S\cdot\ddot{z}+\left(k_{a1}+k_{a2}\right)\cdot\dot{z}+\left(\left(c_{S1}+c_{S2}\right)\right)\cdot z-\\
&-c_{S1}\cdot x_1-c_{S2}\cdot x_2-k_{a1}\cdot\dot{x}_1-k_{a2}\cdot\dot{x}_2=0;\\
&m_1\cdot\ddot{x}_1+\left(k_{W1}+k_{a1}\right)\cdot\dot{x}_1+\left(c_{S1}+c_{W1}\right)\cdot x_1-\\
&-c_{S1}\cdot z-c_{W1}\cdot y_1-k_{a1}\cdot\dot{z}-k_{W1}\cdot\dot{y}_1=0;\\
&m_2\cdot\ddot{x}_2+\left(k_{W2}+k_{a2}\right)\cdot\dot{x}_2+\left(c_{S2}+c_{W2}\right)\cdot x_2-\\
&-c_{S2}\cdot z-c_{W2}\cdot y_2-k_{a2}\cdot\dot{z}-k_{W2}\cdot\dot{y}_2=0.
\end{aligned}\right\}\qquad(11)$$

The system of equations (11) is reduced to the following form that can be implemented in Matlab Simulink (USA):

$$\left.\begin{aligned}
&\ddot{z}=\frac{1}{s}\cdot\begin{bmatrix}-\left(k_{a1}+k_{a2}\right)\cdot\dot{z}-\left(c_{S1}+c_{S2}\right)\cdot z+\\+k_{a1}\cdot\dot{x}_1+c_{S1}\cdot x_1+k_{a2}\cdot\dot{x}_2+c_{S2}\cdot x_2\end{bmatrix};\\
&\ddot{x}_1=\frac{1}{m_1}\cdot\begin{bmatrix}k_{a1}\cdot\dot{z}+c_{S1}\cdot z+k_{W1}\cdot\dot{y}_1+\\+c_{W1}\cdot y_1-\left(k_{W1}+k_{a1}\right)\cdot\dot{x}_1-\\-\left(\left(c_{S1}+c_{W1}\right)\right)\cdot x_1\end{bmatrix};\\
&\ddot{x}_2=\frac{1}{m_2}\cdot\begin{bmatrix}k_{a2}\cdot\dot{z}+c_{S2}\cdot z+k_{W2}\cdot\dot{y}_2+\\+c_{W2}\cdot y_2-\left(k_{W2}+k_{a2}\right)\cdot\dot{x}_2-\\-\left(c_{S2}+c_{W2}\right)\cdot x_2\end{bmatrix}.
\end{aligned}\right\}\qquad(12)$$

The following parameters of the bus are the input to the system of equations (12): coefficients of damping and stiffness of the elastic elements of the front and rear suspensions (k_{a1}=12000 N·s/m, k_{a2}=24000 N·s/m, c_{S1}=450000 N/m, c_{S2}=372000 N/m); coefficients of damping and stiffness of the wheels of the front and rear axles (k_{W1}=27000 N·s/m, k_{W2}=54000 N·s/m, c_{W1}=470000 N/m, c_{W2}=940000 N/m); sprung mass of the bus in the equipped state (M_S=5518 kg); unsprung masses of the bus, respectively, front and rear axles (m_1=328 kg, m_2=554 kg).

Also, the necessary input to the system of equations (12) is to submit specific values of deviations of the microprofile of the road x_i depending on time t. Under the front wheels are the road microprofile values $x_1(t)$, and under the rear wheels – a microprofile of the road $x_2(t)$.

The rear wheels will repeat the microprofile that the front wheels will have passed over time τ [10]:

$$\tau=\frac{l_1+l_2}{V_a},\qquad(13)$$

where V_a – speed of the bus movement; (V_a=40 km/h); l_1, l_2 – distance from the vertical axis of the center of mass of the bus to the vertical axis of the front and rear wheels; $L=l_1+l_2$; (l_1=2.879 m; l_2=1.421 m).

The impact of the road microprofile on the wheels of the front and rear axles is linked via the following dependence [10]:

$$x_1(t)=x_2(t+\tau).\qquad(14)$$

To transfer the bumps of the irregularities created by the microprofile of the road, known dependences of autocorrelation functions of the road microprofile for the following types of road surface were used: asphalt pavement, evenly paved pavement, low-quality paving stones [1]. The coefficients of approximation of the autocorrelation functions of the microprofile of roads were obtained from measuring the microprofile of roads of the above type [1] (Table 1).

Table 1

Coefficients of approximation of autocorrelation functions of the microprofile of roads used in the simulation [1]

Road microprofile	σ_x	A_1	A_2	α_1	α_2	β_2
Asphalt concrete coating	1.03	0.85	0.15	–0.2	–0.05	0.6
Paved paving stones	2.32	1	0	0.45	–	–
Cobblestone of low quality	2.32	0.85	0.15	–0.5	–0.2	1

Dependences [1] are converted into the specific values of the microprofile $x(t)$ using the following formula [1]:

$$x(t)=\zeta(t)\times\times\left[\frac{A_1\cdot\sqrt{2\cdot\sigma_x^2\cdot\alpha_1/h}}{s+\alpha_1}+\frac{A_2\cdot\sqrt{2\cdot\sigma_x^2\cdot\alpha_2/h}\cdot s+A_2\cdot\sqrt{2\cdot\sigma_x^2\cdot\alpha_2/h}\cdot\sqrt{\alpha_2^2+\beta_2^2}}{s^2+2\cdot\alpha_2\cdot s+\alpha_2^2+\beta_2^2}\right],\qquad(15)$$

where $\zeta(t)$ is a discrete white noise; h – integration step; s – differentiation operator; A_1, A_2, α_1, α_2, β_2, σ_x are the coefficients of approximation of the autocorrelation functions of highways.

The corrosion cycle during the operation of the bus is described by dependences, based on the results of the processing of statistical data obtained on the basis of the operation of buses on real routes when transporting passengers in cities with different numbers of inhabitants [10]. The obtained dependences show the dynamics of decrease in the wall thickness of the pipes of the body frame $\Delta_{P>}$ (in cities with more than 1 million inhabitants) and $\Delta_{P<}$ (in cities with the number of inhabitants lless than 1 million) for buses depending on the mileage L. Operation shows that with a service life of up to two years, the body frame and frame do not rust, and their thickness does not change. This is due to the presence of a factory anti-corrosion coating, which is enough for 2 years without updating. Corrosion of the frame and body frame begins to develop intensively. In cities with more than 1 million inhabitants, corrosion will occur more intensively depending on the mileage L according to the dependence of the thickness change: $\Delta_{P>}=6.662\cdot10^{-6}\cdot L+4.33$. With up to 1 million inhabitants, the thickness of the metal will vary according to the dependence: $\Delta_{P<}=2.856\cdot10^{-6}\cdot L+3.57$. More intensity of corrosion of the elements of the bus body frame in cities with more than 1 million inhabitants is explained by the amount of use of salt-sand agents against icing of roads. Also, with a high intensity of passenger traffic in million-plus cities, there is less time for washing buses and eliminating defects in anti-corrosion protection. As the actual operation shows, sometimes buses operated in million-plus cities are not washed for several days.

As a result of solving a system of equations (12) during simulation in Matlab Simulink, the values of movements z of the center of the sprung masses of the bus M_S were obtained.

After finding the second-order derivative from expression (12) in Matlab Simulink, the acceleration of the studied section $\ddot{z}_\Sigma$ was determined.

To determine the forces F caused by vertical movements of the body in the section under study, we use Newton's second law:

$$F_i=M_{S_i}\cdot\ddot{z}_\Sigma.\qquad(16)$$

An important parameter in the study of the accumulation of fatigue strength of the elements of the body frame is the stress σ_i, determined from the following formula:

$$\sigma_i = \frac{F_i}{S_{CS_i}}, \quad (17)$$

where S_{CS_i} – cross-sectional area of the elements of the body frame or frame in the section under study, m^2.

Based on the obtained values of stresses σ_i in the studied cross-section, the values of spectral density $S_0(\omega)$ were calculated, which are used to determine the durability of the bus on the frame chassis in units of mileage according to the Rice formula [10]:

$$S = V_a \times \frac{2\cdot\pi\cdot A}{\Delta^{m_N}\cdot\left(\sqrt{2}\right)^{m_N}\cdot G\left(\frac{m_N+2}{2}\right)\cdot\left(\int\limits_{\omega} S_0(\omega)\cdot\omega^{\frac{2}{m_N}}\mathrm{d}\omega\right)^{\frac{m_N}{2}}}, \quad (18)$$

where V_a is the average speed of the bus; $\Delta=\sqrt{D}$ – standard deviation of the current values of stresses σ_i; D – variance; $S_0(\omega)=S(\omega)/D$ – the reduced spectral density of the action of stresses σ_i; $G\left(\frac{m_N+2}{2}\right)$ – gamma function; A and m_N – characteristics of the endurance curve $\left(A=N\cdot\sigma_a^{m_N}\right)$.

To assess the durability of the bus body with the help of simulation, a modern bus was selected on the frame chassis «Etalon» BAZ-A079, the necessary parameters of which were entered into the developed mathematical model (entered into the Script file, the data of which are entered into the Matlab Simulink working area before starting the simulation), implemented in the software environment Matlab Simulink. The calculation of durability was carried out when simulating traffic in a million-plus city with the maximum technically permissible workload of passengers (40 passengers), the average speed of 40 km/h, on different microprofiles of the road surface: asphalt pavement, evenly paved pavement, low-quality paving stones.

5. Results of assessing the durability of the bus body on a frame chassis using an improved procedure

5. 1. Conceptual solutions for improving the procedure for determining the durability of bus bodies on a frame chassis

To improve the procedure reported in [1], which involves determining the durability of the body with a load-bearing structure, the design features of the bus on the frame chassisaare were taken into account. It is also important to determine the durability of both the frame and the body attached to the frame. For the study, one of the sections of the frame at the place of attachment of the body is selected, which will be destroyed first. As shown by many years of experience in the operation and repair practice of buses, such sections are located in places that are as close as possible to the fastening of the bus springs and in places where the body frame fits to the frame. which is also confirmed by road tests [10]. Fig. 1 shows the distance l_i from the vertical axis of the center of mass of the bus z to the studied section, which is shown in Fig. 2.

In contrast to the methodology developed earlier [1], where the cross-section of the homogeneous material of the base frame was investigated, this study involves testing the cross-section of two materials with different properties (Fig. 2).

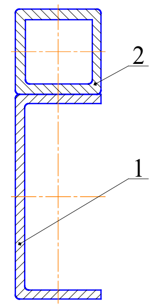

Fig. 2. The studied cross-section of the bus body on the frame chassis: 1 – frame; 2 – body frame element

The studied cross-section consists of frame 1, which is made of alloy steel and has an open structure. As the experience of operating buses shows, unlike closed-type pipes, the open-type frame has a higher corrosion resistance, by 1.5–1.7 times (1.6 is taken into account). This is due to the use of alloy steel and an open frame structure that is better ventilated and does not allow condensate to accumulate. Thus, the studied cross-section during simulation is divided into 2 elements: frame section 1 and frame section 2. As the real operation shows, the element of the body frame must be destroyed first, and then, after a certain period of operation, the frame is destroyed.

Existing procedure [1] is improved by the fact that the calculation of durability instead of a homogeneous material of the studied cross-section with the same-sign corrosion flow according to the dependence that describes the corrosion process depending on the number of inhabitants in the city, is replaced by two different processes that occur differently for the body frame (p. 2, Fig. 2) and frame (p. 1, Fig. 2). In the beginning of simulation, it is assumed that elements 1 and 2 (Fig. 2) work as a whole only with different changes in the cross-sectional area under the action of corrosion. After the destruction of element 2 of the body frame, the study will continue only with element 1. Procedure [1] involves simulation when transferring bumps from the microprofile of the road to the body through the front spring suspension and rear spring-pneumatic suspension. The considered bus on the frame chassis has all the spring suspensions. Methodology [1] has been improved in such a way that it becomes universal for different types of suspensions and, with the help of simulation, could be used to conduct research on buses with different types of suspensions.

5. 2. Results of assessing the durability of a bus body on the frame chassis using computer simulation

Fig. 3 shows a simulation model in Matlab Simulink, based on the developed approach to assessing the durability of a bus body on the frame chassis, which makes it possible to implement the solution of a system of equations (12) in determining the stresses in the studied section of the frame and body frame. Here, at the input, equation (15) is implemented using the subroutine «Subsystem 1» [1], according to which the coefficients of autocorrelation functions of highways are recalculated (Table 1) into specific values of deviation of inequalities according to the integration step. Using the subroutine «Sybsystem 2», the cross-sectional area of the frame and body frame is calculated, which will vary depending on corrosion, which depends on the mileage and the number of residents of the city in which the bus is operated.

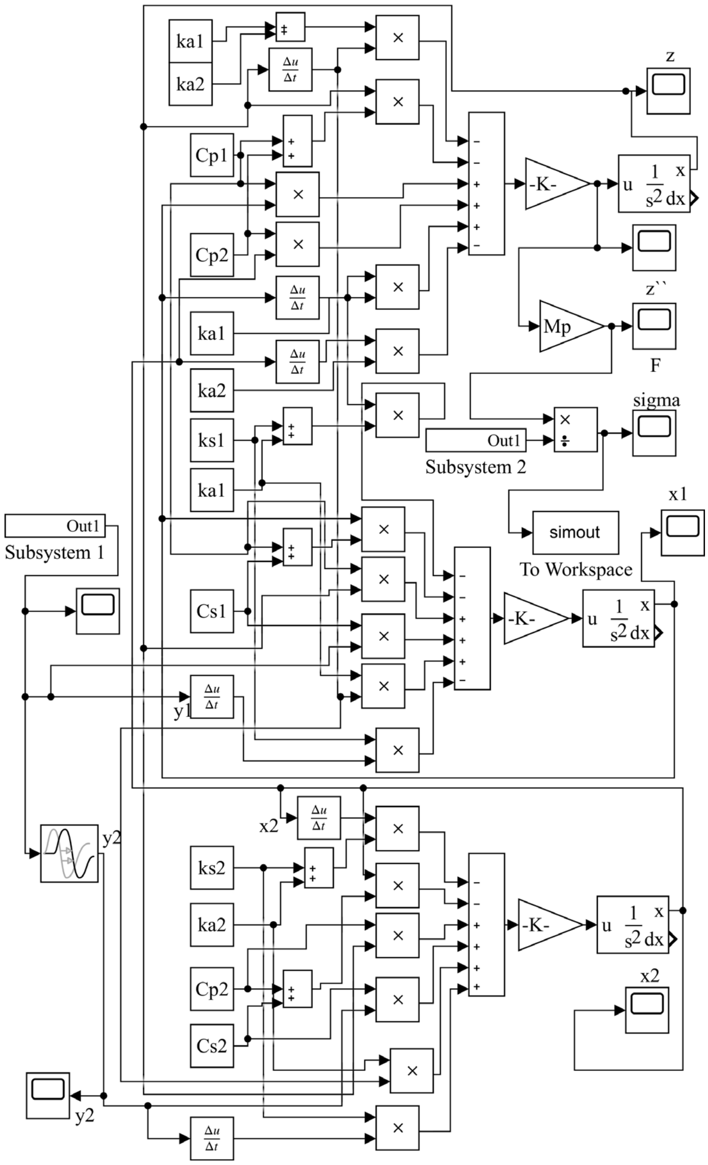

Fig. 3. Simulation model in Matlab Simulink, based on the developed approach to assessing the durability of A bus body on the frame chassis

At the output, stress values are obtained in the studied section of the frame and/or frame of the «sigma» body, which are displayed in the Matlab Simulink working area using the «To Workspace» block in the form of an array. Based on the data of the array, the reduced spectral density $S_0(\omega)$ is calculated, which makes it possible to determine the durability of the body and frame using formula (18) already using the previously developed part of the model in Matlab Simulink [1, 10].

Fig. 4 shows the implementation of the model in the subroutine «Subsystem 2», which is created on the basis of the developed approach to assessing the durability of a bus body on the frame chassis and makes it possible to calculate the areas of the studied sections.

Fig. 4 demonstrates that the model used eearlier [1] is highlighted and has the name: «Calculation of the cross-section of body 1 frame». This model is supplemented with the corresponding blocks of the model, which made it possible to calculate the cross section of the frame («Calculation of the section of the frame») and the calculation of the cross-section of the body frame («Calculation of the cross-section of body 2 frame») both separately and the total cross-section of the frame with the frame. If the values «0» or «1» are fed to the control inputs of the model blocks: «Switch 3», «Switch 5» in different combinations, the desired cross-section will be calculated. The RAMAKUZOW=0 value and any RAMA value at the output «1» of the subroutine «Subsystem 2» will calculate the studied cross-section of the body frame. After the input of value RAMAKUZOW=1 and the RAMA=1 value, the output «1» of the subroutine «Subsystem 2» will calculate the studied section of the frame. The RAMAKUZOW=1 value and the RAMA=0 value at the output «1» of the subroutine «Sybsystem 2» will calculate the studied total cross-section of the frame and body.

Thus, Fig. 3, 4 show those components of the model that have undergone changes in the development of an approach to assessing the durability of the bus body on the frame chassis.

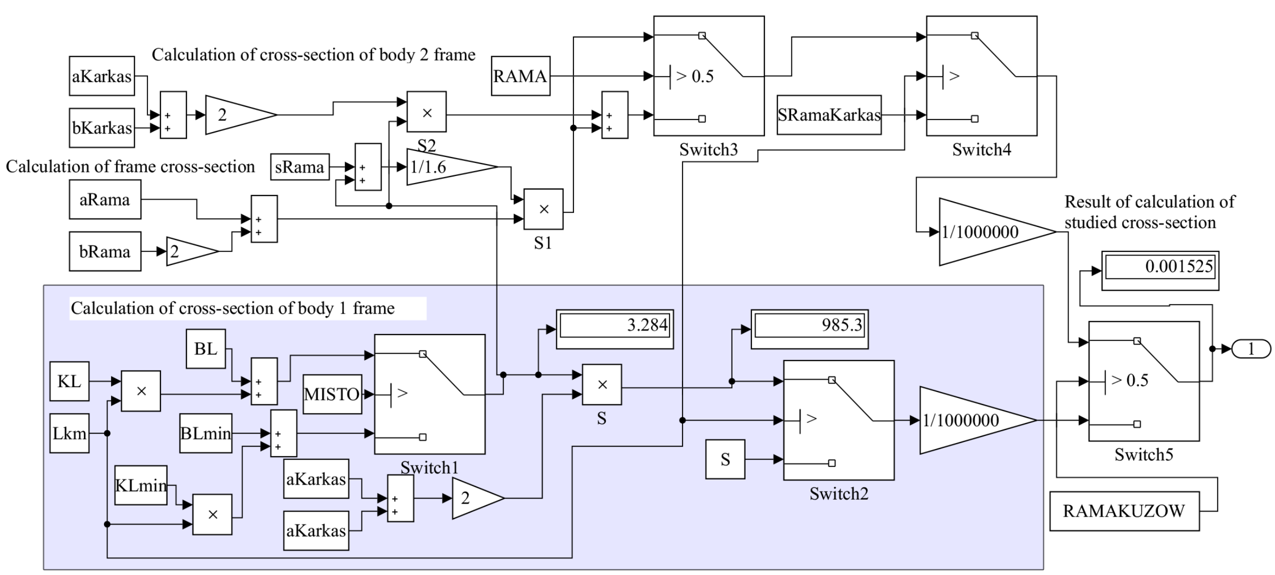

Fig. 4. Implementation of the subroutine «Subsystem 2» in Matlab Simulink

At the time of simulation, the results were obtained, which are given in Table 2.

Table 2

Results of assessing the durability of the body of the bus «Etalon» BAZ-A079 on the frame chassis

Road microprofile	Durability of the body frame, km	Durability of the frame, km
Asphalt concrete coating	1376970	2478532
Paved paving stones	907653	1452406
Cobblestone of low quality	493452	838870

Table 1 gives the results with an average speed of 40 km/h and a maximum allowable load by passengers (40 passengers).

On the basis of the obtained data on the results of simulation, the dependence of the durability of the body frame (on the frame chassis) and frame on the type of road surface (microprofile of the road) was established (Fig. 5).

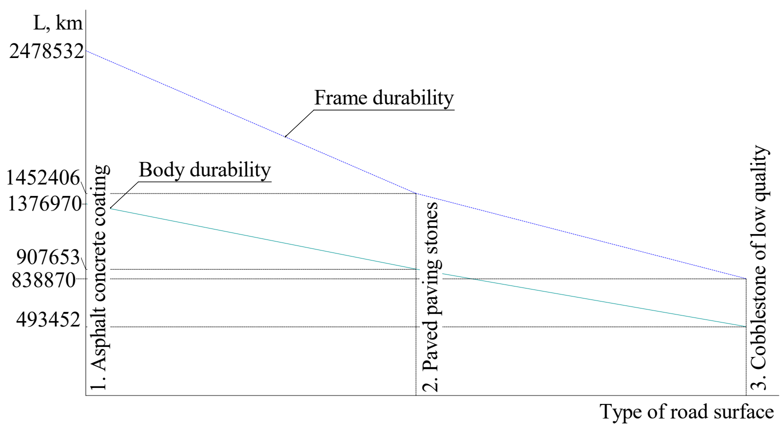

Fig. 5. Dependences of durability of the body frame and frame of the bus «Etalon» BAZ-A079 on the type of road surface

Graphic dependences shown Fig. 5 confirm the durability of the bus frame in real operation, which exceeds the body life by about 1.5–1.8 times. When comparing with the actual operating conditions while buses are operated on roads of different quality (asphalt pavement, evenly paved pavement, low-quality paving stones), the durability of the frame does not exceed 1.5 million km, and the body under such conditions of operation has a durability in the range of 750–800 thousand km. The results allow us to predict the durability of the bus body on the frame chassis both during operation (depending on operating conditions) and at the design stage. Therefore, it becomes possible to lay a potential resource by changing materials, their cross sections and anti-corrosion protection technologies.

6. Discussion of results of assessing the durability of a bus body on the frame chassis

Conceptual solutions to improve the methodology for determining the durability of bus bodies on the frame chassis allow for the study of buses not only with a load-bearing structure but also on the frame chassis.

As a result of our study, the durability of the bus body on the frame chassis with different types of road surface was determined. Table 1 and Fig. 3 show that the maximum durability values will be demonstrated by the bus frame; they exceed the durability of the body by 1.5–1.8 times. Given this, our results confirm the experience of actual operation of buses. Such results confirm the assumption that a frame made of alloy steel and an open structure with better ventilation will have greater durability. Conversely, the body frame made of steel pipes of a closed structure will corrode more intensively due to moisture condensation in closed cavities. We also have logical confirmation of the durability of the body frame and frame while improving the quality of the road surface. The higher the quality of the road surface, the smaller deviations will be from its microprofile, and the smaller bumps will be transmitted through the sprung masses m_1 and m_2 to the frame and body frame.

In contrast to [1], where the calculation of the durability of buses only with a load-bearing structure was carried out, the improved procedure makes it possible to calculate the durability of the bus body with a frame structure. This becomes possible due to taking into account the design features of buses on frame chassis. This study takes into account the geometric dimensions of the frame sections, its physical and mechanical properties, and the peculiarities of corrosion during operation. It is confirmed that with corrosion and fatigue destruction of the body frame, the intensity of fatigue destruction of the frame increases.

The improved methodology and the reported studies allow us to determine the durability of the bus on a frame chassis that simulates the actual operating conditions. This makes it possible to assess the durability of the bus for operating organizations and carry out scheduled repairs. Also, at the design stage, it is possible to develop new technical solutions to improve corrosion resistance of the body frame, the durability of which is still 1.5–1.8 times less than the frame durability.

A rational option would be such a design of the body frame, the durability of which would be equal to the durability of the body. Thus, the improvement of methods of anti-corrosion protection of the body frame at the stage of ddesign and periodic additional protection of its closed cavities will make it possible to bring the durability of the body frame to the durability of the frame.

The limitation of our study is that this procedure and results apply only to buses on a frame chassis. There may also be no characteristics on the corrosion intensity of the body pipe frame made of other materials and with other methods of corrosion protection.

The disadvantages of these studies may refer to the lack of information on the physical and mechanical properties of frames that can be supplied with new machine kits of foreign production. It is also possible that there are no statistical dependences on corrosion damage to the body frame when using new progressive corrosion protection products.

The development of this study may involve laboratory tests of new materials in order to determine their physical, mechanical, and resource characteristics of samples. One also needs to accumulate statistics on the corrosion resistance of bus bodies with certain improvements in corrosion protection. It would also be advisable to conduct accelerated tests of samples in order to determine the intensity of corrosion and obtain mathematical dependences for inclusion in the simulation model. It is also possible to study in which an array of data on the relative deformations of the studied section on a specific route is obtained using portable strain gauge stations.

7. Conclusions

1. The methodology for determining the durability of the bus body with a load-bearing structure has been improved for the possibility of conducting research on buses with a frame chassis. The proposed conceptual solutions take into account the operation of the body frame on a frame chassis during simulation, which was not possible before. It takes into account the physical and mechanical characteristics of the frame, its geometric dimensions, and the dependences of decrease in the thickness of the frame material. This procedure to determine the durability of bus bodies on frame chassis makes it possible to improve the design of buses and positively affect their durability without conducting high-cost full-scale resource tests.

2. The assessment of the durability of the bus body on a frame chassis was performed using simulation computer modeling, which is in the range from 5 to 11 years depending on the operating conditions. The following factors were taken into account in the study: passenger occupancy, microprofile of the road, the speed of the bus movement, corrosion. The durability of the bus depends on the durability of the frame and body frame. Since the frame is made of alloy steels and heat-treated, when cracks in the frame are formed, it is not repaired but replaced with a new one. It was found that the frame has 1.5–1.8-time larger durability than the body frame itself. This is explained by the fact that the frame is made of alloyed materials and has an open structure that provides better ventilation. The results of our research indicate the primary improvement of the anti-corrosion protection of the body frame in order to bring its resource closer to that of the frame.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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References

1. Ruban, D., Kraynyk, L., Ruban, H., Sosyk, A., Shcherbyna, A., Dudarenko, O., Artyukh, A. (2021). Forecasting the durability of public transport bus bodies depending on operating conditions. Eastern-European Journal of Enterprise Technologies, 4 (1 (112)), 26–33. doi: https://doi.org/10.15587/1729-4061.2021.238171
2. MathWorks. Available at: https://www.matlab.com/
3. Ruban, D., Kraynyk, L., Ruban, H., Hrubel, M., Duzhyi, R., Babaryha, A. (2022). Development of technological principles of technical control of bus bodies during operation based on passive safety conditions. Eastern-European Journal of Enterprise Technologies, 6 (1 (120)), 91–100. doi: https://doi.org/10.15587/1729-4061.2022.268178
4. Regulation No 66 of the Economic Commission for Europe of the United Nations (UN/ECE) – Uniform provisions concerning the approval of large passenger vehicles with regard to the strength of their superstructure. Available at: http://data.europa.eu/eli/reg/2011/66(2)/oj
5. Farahani, B. V., Ramos, N. V., Moreira, P. M. G. P., Cunha, R., Costa, A., Maia, R., Rodrigues, R. M. (2022). Passive Safety Solutions on Transit Buses: Experimental and Numerical Analyses. Procedia Structural Integrity, 37, 668–675. doi: https://doi.org/10.1016/j.prostr.2022.01.136
6. Boutar, Y., Naïmi, S., Mezlini, S., Carbas, R. J. C., da Silva, L. F. M., Ali, M. B. S. (2021). Cyclic fatigue testing: Assessment of polyurethane adhesive joints' durability for bus structures' aluminium assembly. Journal of Advanced Joining Processes, 3, 100053. doi: https://doi.org/10.1016/j.jajp.2021.100053
7. Kepka, M., Kepka, M., Václavík, J., Chvojan, J. (2019). Fatigue life of a bus structure in normal operation and in accelerated testing on special tracks. Procedia Structural Integrity, 17, 44–50. doi: https://doi.org/10.1016/j.prostr.2019.08.007
8. Kepka, M., Kepka, M., Dzugan, J., Konopik, P. (2019). Practical notes for assessing the fatigue life of bodyworks of buses and trolleybuses. Procedia Structural Integrity, 19, 595–603. doi: https://doi.org/10.1016/j.prostr.2019.12.064
9. Kepka, M., Kepka, M. (2020). Accelerated fatigue testing on special tracks as new part of methodology for bus/trolleybus development. Engineering Failure Analysis, 118, 104786. doi: https://doi.org/10.1016/j.engfailanal.2020.104786
10. Ruban, D. P. (2020). Mathematical Model of Forecasting Durability of Bus Bodies and Checking it for Adequacy. Visnyk of Vinnytsia Politechnical Institute, 150 (3), 81–89. doi: https://doi.org/10.31649/1997-9266-2020-150-3-81-89