PREDICTIVE ASSESSMENT OF BUS BODY LIFE IN THE MATLAB SIMULINK SOFTWARE ENVIRONMENT

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Resume

The lifespan prediction of the bus body of the load-bearing structure has been made and compared to the results of real operation. The maximum approximation of the simulation modelling results in Matlab Simulink to real operation is explained by taking into account a sufficient number of factors influencing durability. This research has the particularity that it allows determining the durability of the bus body even at the design stage, which was not possible with accelerated tests or during the operation of the bus on real routes. The obtained results can be used by bus manufacturers at the design stage, allowing them to change the construction and technology of anticorrosion protection, thereby influencing the durability. In addition, operating organizations will be interested in the obtained results when using the developed methodology in various operating conditions.

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1 Introduction

Usually, to determine the durability of a bus body, accelerated durability tests are carried out on routes that can be as close as possible to real operating conditions. Given that the durability of the bus body can reach 1 million km, such durability tests require significant time and costs. Therefore, bus factories may neglect such resource tests, referring to the durability of previous similar models of buses. As a result, the bus begins operation, during which the durability of buses of this model can be tracked for 5-10 years. However, over such a long period, the results of durability tests may become irrelevant. Moreover, it is impossible to accurately track the roads on which these buses were operated, as well as with what loads (overloads) of passengers the buses were moving on those roads. During the development of new bus models for manufacturers, it is important to know how certain materials in combination with anti-corrosion protection technologies will affect its durability. By predicting the durability of a bus when using various structural materials, manufacturing technologies, and anti-corrosion protection of the body, it is possible to influence the durability of the body at the design stage.

Today, it has become possible to conduct durability testing of buses using simulation modelling methods, due to the development of modern applications. One such program is the Matlab Simulink software environment (USA). Matlab Simulink allows for the simultaneous solution of systems of differential equations. In this process, the spectral density of the road microprofile is transformed into real deviations of the microprofile, and stresses are formed in the investigated cross-section at the output in the form of spectral density, which allows calculating the body's durability using known dependencies.

Scientific research on this topic is important because it becomes possible to conduct simulation modelling countless times, taking into account various operating conditions, body materials, and anti-corrosion protection technologies.

The results of such research are necessary for practice, as they open up new opportunities in designing bus bodies with the influence of new design solutions on its durability even at the design stage without significant costs.

Thus, prognostic evaluation in the Matlab Simulink software environment will allow for improving the design of bus bodies by influencing the body's lifespan already at the design stage. Additionally, operating organizations can forecast the lifespan depending on operating conditions and predict when it is advisable to perform restorative repairs on the body at a particular mileage in the future.

The work [1] presents a mathematical model for predicting the service life of bus bodies. It is shown that when tested for adequacy, the model has a right to exist. However, there are unresolved issues related to the absence of a description of suspension punctures in the model, which often occur when driving on low-quality roads. The reason for this may be the lack of classical calculation methods in the "road-vehicle" systems, which would allow for a more realistic description of the movement of buses on roads with potholes. One way to overcome these difficulties may be to take into account the suspension punctures by applying new dependencies. Such an approach is used in work [2], which maximally approximates the movement of a bus on low-quality roads (low-quality pavement), but does not directly take into account suspension punctures. The work [2] also investigates the durability of non-bearing bus structures, but similar research on frame-type buses is not performed. One way to overcome such difficulties may be to study the durability of the frame-type buses, as well. Such an approach is used in work [3]. However, here only compliance with UN Rule No. 66 on passive safety is checked during the operation of frame-type bus bodies. The authors [4] suggest using calculation methods with the use of simulation modelling instead of natural experiments when checking compliance with the Rule [5] for buses. However, in work [4], the research only concerns new buses without taking into account the degradation of the bus body material. In work [4], confirmation of the use of simulation modelling is important, which significantly simplifies the work and reduces the cost of conducting an experiment. Work [6] describes methods for studying the transmission of disturbances from the micro-profile of the road surface to the body of a new car. However, here again, the deterioration of the properties of the body material during the operation is not taken into account. Further development of work [6] may be the consideration of the degradation of car body elements. The article [7] describes methods for studying the road surfaces, which can be used to investigate the influence of road micro-profile on the bus body.

The paper [8] explains how corrosion processes in bus bodies increase losses during the passenger transportation. Therefore, when making a predictive assessment of bus bodies, it is also important to take into account the corrosion processes during the operation of public transport buses.

The methodology for determining the passenger load [9] can be useful in predicting the number of passengers during the bus operation. Such an approach [9] will allow for more realistic research on the durability of public transport buses.

As a result of the analysis of studies [10-14], it was found that accelerated durability tests were conducted using laboratory stands. However, such studies did not take into account the corrosive processes that have a significant impact on the durability of the bus.

All of this allows us to assert that it is expedient to conduct research dedicated to the predictive assessment of the bus body durability using simulation modelling.

The aim of the research was to make a prognostic assessment of the bus body durability using Matlab Simulink software. This will allow predicting the durability of the body through simulation modelling without conducting long-term, high-cost durability tests on buses in real operation.

The following tasks were set to achieve the goal:

- develop a methodology for prognostic assessment of the body structure durability of a bus with a non-bearing and frame structure;
- implement the developed methodology in Matlab Simulink software, taking into account suspension failures;
- conduct simulated modelling of the durability of non-bearing and frame structure bus bodies and compare them.

2 Materials and methods

The object of the research was the permissible limits of aging of bus bodies during operation and the possibility of forming recommendations for bodybuilding design under the conditions of regulated body durability.

The main hypothesis of the study is that simulation modelling using modern applications allows for forecasting the resource of bus bodies through the mathematical description of the impact of road micro-profile, passenger load, speed, and corrosion on the body.

The assumptions adopted in the study indicate that the bus body's durability is influenced by corrosion and road microprofile impacts combined with passenger loading and bus speed. The punctures in the suspension, which inevitably occur when driving on low-quality roads, overloading, and increased bus speed, also play an important role in simulation modelling.

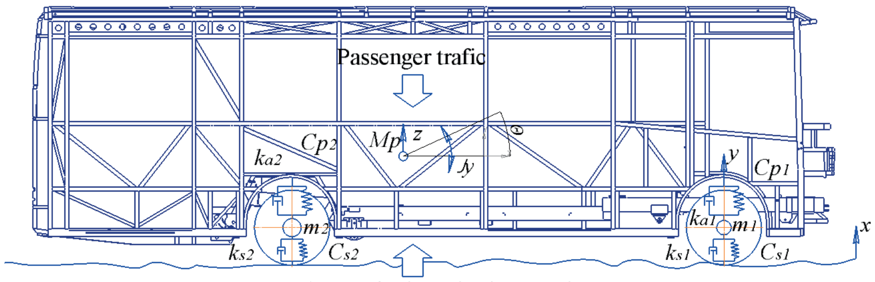

***Figure 1** Calculation scheme*

The simplifications adopted in the study involve the use of simulation modelling instead of conducting the long and high-cost durability tests on buses.

To conduct the prognostic assessment of the bus body durability, the Matlab Simulink 2017b software environment (USA) [15] was chosen. Matlab [15] is a high-level programming language designed for engineers and scientists that directly expresses matrix and array mathematics. Matlab can be used for everything, from performing simple interactive commands to developing large-scale applications. Thus, Matlab Simulink allows solving the tasks related to determining the durability of the bus body, taking into account the selected factors.

The predictive assessment methodology of the bus body durability of the non-load bearing and frame structure is implemented as follows. The durability of the bus body and frame is influenced by a number of factors. The main ones include micro-profile of the road, passenger loading, bus speed, and corrosion. Passenger loading is selected within the limits corresponding to operating conditions, taking into account possible overloads. That is, the minimum number will correspond to the number of passengers occupying all the seats. The maximum number of passengers will correspond to the number corresponding to one and a half times the overload. It should be noted that in the design practice of developing the bus bodies, an overload factor equal to 1.7 is assumed. Bumps from micro-profile irregularities on the road are transmitted through the bus wheels and suspension to the frame and/or bus body. The strength of shocks from the road will increase as the speed of the bus increases and deviations from the micro-profile of the road increase. For buses on a frame chassis, forces are transmitted to the body through the frame. In buses with non-load-bearing bodies, forces from the suspension are transmitted directly to the body. The damping and elastic properties of the tires and suspensions directly affect the transmission of forces from the micro-profile of the road to the bus body. To describe the process of converting the action of the micro-profile of the road into the bus body, the second-order Lagrange equation [16] should be used. In this case, in addition to disturbing and potential forces, there are also resistance forces acting on the dynamic system, so the Lagrange equations will take the form:

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

- where $k = 1, 2, \dots, n$;
- n is the number of degrees of freedom of the dynamic system (the proposed mathematical model will have four degrees of freedom);
- T is the kinetic energy of the system;
- P is the potential energy of the system;
- F is a scattering function (Rayleigh function);
- q_k is the k-th generalized coordinate.

This dynamic system has only two degrees of freedom, and its position in space is determined by the two generalized coordinates $q_1 = x$ and $q_2 = z$. However, for the full implementation of the mathematical model describing the movement of the bus in real operating conditions, a dynamic system describing four degrees of freedom must be used.

Consider the vertical and longitudinal-angular fluctuations of the sprung masses of the bus M_p and unsprung masses m_1 and m_2 relative static equilibrium according to the calculation scheme (Figure 1).

$$\left.\begin{aligned} T &= \frac{1}{2}(M_p \cdot \dot{z}^2 + J_y \cdot \dot{\Theta}^2 + m_1 \cdot \dot{x}_1^2 + m_2 \cdot \dot{x}_2^2); \\ P &= \frac{1}{2}\begin{bmatrix} c_{s1}(y_1 - x_1)^2 + c_{s2}(y_2 - x_2)^2 + \\ + c_{p1}(x_1 - z - \Theta \cdot l_1)^2 + \\ + c_{p2}(x_2 - z + \Theta \cdot l_2)^2 \end{bmatrix}; \\ F &= \frac{1}{2}\begin{bmatrix} k_{s1}(\dot{y}_1 - \dot{x}_1)^2 + k_{s2}(\dot{y}_2 - \dot{x}_2)^2 + \\ + k_{a1}(\dot{x}_1 - \dot{z} - \dot{\Theta} \cdot l_1)^2 + \\ + k_{a2}(\dot{x}_2 - \dot{z} - \dot{\Theta} \cdot l_2)^2 \end{bmatrix}; \end{aligned}\right\} \tag{2}$$

- where l_1 and l_2 are the distances from the vertical axis of the center of mass of the bus to the vertical axis of the front and rear wheels, respectively; $L = l_1 + l_2$;
- J_y is the moment of inertia of the sprung mass of the bus performing longitudinal and angular oscillations;
- Θ is the angle by which the bus deviates from the horizontal axis during longitudinal-angular oscillations.

All the three functions in Equations (2) are sign-changing positive quadratic forms of the velocities,

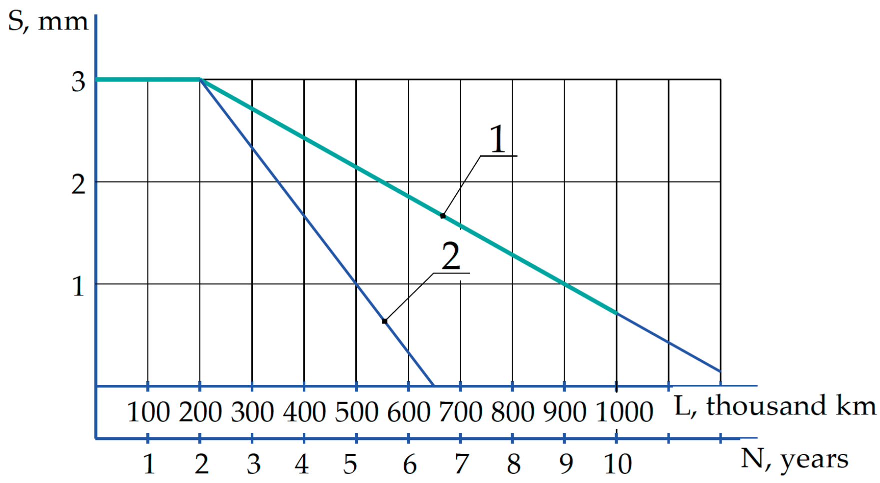

***Figure 2** Graphical dependence showing the decrease in the thickness of the walls S of the base frame, which decreases with an increase in the service life N and an increase in the bus mileage L [2]: 1 - in cities with up to one million inhabitants; 2 - in the metropolises*

coordinates of the vertical wheel displacements of the bus, vertical displacements and longitudinal-angular oscillations of the bus body.

After differentiating the system of Equations (2), the results of differentiation are substituted into the Lagrange Equation (1).

It should also be noted that the rear wheels will repeat the microprofile of the road with a time lag. This time lag is obtained by dividing the wheelbase of the bus L by its speed V_a.

Thus, the values from the road microprofile will be fed into the input of the obtained system of equations. It is assumed that the microprofile under the wheels of one axis is the same. This simplification indicates that there will be no lateral angular oscillations during the bus movement. The values of the road microprofile can be obtained based on spectral densities that were previously studied on special test tracks. In addition, the parameters of the road microprofile can be obtained on a real route on which the bus moves, the durability of the body of which is determined.

As a result of solving the obtained system of equations in Matlab Simulink, the vertical acceleration of the bus's center of mass $\ddot{z}$ can be obtained. Then this value can be brought to the cross-section that limits the durability of the bus body. Typically, such cross-sections are located near the mounts of suspension elements (points 1 and 2 in Figure 1). The force F_i, that arises in the cross-section is determined by the second Newton law. Then, having found the force F_i, and knowing the area of the investigated cross-section of the body frame or frame, the stress σ_i can be determined.

During the operation of the bus, the cross-sectional area of the body frame elements will constantly decrease due to corrosion. The characteristics of the reduction in wall thickness of the body frame elements are obtained based on statistical data from the operation of buses of a similar class. The intensity of corrosion will depend on the operating conditions and anti-corrosion protection. Experience shows that during the first two years of operation, the body frame elements hardly corrode due to the factory anti-corrosion protection. In accordance with the improvement of manufacturing technology and the use of advanced anti-corrosion materials, it is possible to achieve such a level of anti-corrosion protection that the body frame will be protected from corrosion during longer periods of operation (more than two years). However, after that, intensive corrosion of the body frame elements begins because the operating organizations do not renew the worn-out factory anti-corrosion protection. The use of the road deicing agents has a significant effect on the intensity of corrosion. The more roads are sprayed or sprinkled with such reagents, the more the thickness of the body frame elements decreases. Bus operating experience shows that in large cities with a population of over 1 million, the reduction in the thickness of the body frame elements is almost twice as intensive as in small cities. Figure 2 shows the regularities of the change in the thickness of the bus base frame pipes during operation.

The data shown in Figure 2 are obtained on the basis of statistical data obtained from the data of the repair practice of operating organizations as a result of the operation of buses in cities with a population of up to one million or more (this technology can be taken as basic). Additionally, with the improvement of manufacturing technology and the use of advanced anti-corrosion materials, the wall thickness of the body frame pipes will remain unchanged for more than two years. It will be possible to evaluate new technical solutions for improving the corrosion resistance as a result of durability laboratory studies comparing the impact of an aggressive environment on existing and improved samples. In this way, it is possible to obtain correcting coefficients depending on the degree of improvement of the basic technology.

The proposed methodology also involves determining the stress σ_i in the investigated cross-section using the strain gauging. This means that sensors are attached to the investigated cross-section and the corresponding signal is transformed and transmitted to a laptop using a portable strain gauge. This allows for obtaining a series of stress data and converting it into the spectral density of stresses corresponding to a specific route under specific operating conditions. This method of stress determination, on the one hand, allows for a more accurate calculation of the bus body's durability for specific operating conditions on the chosen route, and on the other hand, prevents the correction of the body structure and research into the influence on the durability_ at the design stage. The driving technology can be evaluated by the average speed on the route, which allows the research to be brought closer to real operating conditions.

To determine the durability of the bus body over time, the Reichert formula [17] has been chosen, which involves substituting the spectral density of stress in the investigated cross-section and the characteristics of the endurance curve of the investigated material. At the selected average speed of the bus, the durability of its body is determined in units of mileage.

3 Results of the assessment of the durability of the bus body in the Matlab Simulink software environment

3.1 Implementation in the Matlab Simulink software environment of the methodology for prognostic the assessment of the durability of the bus body taking into account suspension breakdowns

The system of blocks in the Matlab Simulink software environment allows to build an algorithm for solving a system of equations. This algorithm makes it possible to bring the vertical and longitudinal-angular movements of the bus body to vertical movements in the studied section. As a result of substituting the differentiated System of Equations (2) into the Lagrange Equation (1), the resulting system of equations is reduced to a convenient form in Equation (3) for solving in Matlab Simulink.

In operating conditions, taking into account the quality of the road surface, punctures of the bus suspension inevitably occur. The puncture of the suspension is accompanied by the contact of the bumpers with the corresponding suspension elements. In particular, in the "Ataman" A092N6 buses, the puncture of the front suspension is accompanied by contact with the bumper, and the rear suspension punctures upon contact with the buffers inside the pneumatic spring. When the suspension is punctured, it begins to work as a whole with the sprung mass of the body and does not perform its function. Thus, alternating loads from the road microprofile will be transmitted, taking into account only the energy absorption by the tires, directly to the sprung mass of the bus body. When the suspension (unsprung mass) works as a whole with the body (sprung mass), the stiffness coefficient c_{pi} reaches its maximum value and tends to infinity.

$$\left[\begin{array}{l}
\ddot{z}=\dfrac{1}{M_p}\cdot\left[\begin{array}{l}-(k_{a1}+k_{a2})\cdot\dot{z}-(c_{p1}+c_{p2})\cdot z+\\+k_{a1}\cdot\dot{x}_1+c_{p1}\cdot x_1+k_{a2}\cdot\dot{x}_2+c_{p2}\cdot\\\cdot x_2+(k_{a2}\cdot l_2-k_{a1}\cdot 1)\cdot\dot{\Theta}+\\+(c_{p2}\cdot l_2-c_{p1}\cdot l_1)\cdot\Theta\end{array}\right];\\
\ddot{\Theta}=\dfrac{1}{J_y}\cdot\left[\begin{array}{l}(k_{a2}\cdot l_2-k_{a1}\cdot l_1)\cdot\dot{\Theta}+(c_{p2}\cdot l_2-\\-c_{p1}\cdot l_1)\cdot(k_{a1}\cdot l_1^2+k_{a2}\cdot l_2^2)\cdot\dot{\Theta}-\\-(c_{p1}\cdot l_1^2+c_{p2}\cdot l_2^2)\cdot\dot{\Theta}-(c_{p1}\cdot l_1^2+\\+c_{p2}\cdot l_2^2)\cdot\Theta+k_{a1}\cdot l_1\cdot\dot{x}_1+c_{p1}\cdot\\\cdot l_1\cdot x_1-k_{a2}\cdot l_2\cdot\dot{x}_2-c_{p2}\cdot l_2\cdot x_2\end{array}\right];\\
\ddot{x}_1=\dfrac{1}{m_1}\cdot\left[\begin{array}{l}k_{a1}\cdot\dot{z}+c_{p1}\cdot z+k_{s1}\cdot\dot{y}_1+c_{s1}\cdot\\\cdot y_1-(k_{s1}+k_{a1})\cdot\dot{x}_1-(c_{s1}+c_{p1})\cdot\\\cdot x_1(k_{a1}\cdot\dot{\Theta}+c_{p1}\cdot\Theta)\cdot l_1\end{array}\right];\\
\ddot{x}_2=\dfrac{1}{m_2}\cdot\left[\begin{array}{l}k_{a2}\cdot\dot{z}+c_{p2}\cdot z+k_{s2}\cdot\dot{y}_2+c_{s2}\cdot\\\cdot y_2-(k_{s2}+k_{a2})\cdot\dot{x}_2-(c_{s2}+c_{p2})\cdot\\\cdot x_2(k_{a2}\cdot\dot{\Theta}+c_{p2}\cdot\Theta)\cdot l_2\end{array}\right];
\end{array}\right], \quad (3)$$

To cause the suspension failure, it is necessary for the product of acceleration of the unsprung mass by the unsprung mass itself (force towards the body caused by road micro-profile irregularities) combined with the load of the distributed sprung mass on the given unsprung mass (load of the bus's sprung mass with passengers, which compresses the suspension's elastic elements), to be equal to or greater than the suspension's spring force (product of the stiffness coefficient c_{pi} and displacement up to suspension failure).

The condition for suspension failure can be expressed as follows:

$$\text{when } m_i\cdot\ddot{x}_i+M_{Pi}\geq F_{PPi},\quad c_{Pi}=c_{Ppri}\rightarrow\infty; \quad (4)$$

$$\text{when } m_i\cdot\ddot{x}_i+M_{Pi}<F_{PPi},\quad c_{Pi}=\text{const},$$

- where $m_i\cdot\ddot{x}_i$ is force in the direction of the body, caused by the irregularities of the micro-profile of the road through the *i*-th suspension;
- M_{Pi} - the load of the sprung mass of the bus with passengers compressing the elastic elements *i*-th suspension; $(M_P=M_{P1}+M_{P2})$;
- F_{PPi} is the elastic force of the *i*-th suspension;
- $F_{PPi}=c_{Pi}\cdot x_{Pi}$;
- $F_{PP1}=c_{P1}\cdot x_{P1}$ is the elastic force of the front suspension;
- $F_{PP2}=c_{PRes}\cdot x_{P2}+F_{PBal}$ is the elastic force of the rear suspension (with springs and pneumatic cylinders);
- c_{PRes} is the stiffness coefficient of the rear springs;

- F_{PBal} is the maximum elastic force of the pneumatic cylinder;
- c_{PPri} is the stiffness coefficient of i- th suspension in the event of a failure;
- x_{Pi} is the displacement of the i-th suspension before the failure.

The condition in Equation (4) is implemented in the Matlab Simulink software environment as follows. A subsystem is created, and using the blocks in the Simulink library, the given algorithm is solved. All the necessary variables for calculation are specified in the Matlab workspace and are also taken from the calculation of the System of Equations (3). For example, Figure 3 shows the implementation of the algorithm for the front suspension failure.

The "IN" (Figure 3) receives calculated forces in the direction of the body, caused by the irregularities of the micro-profile of the road through the front suspension $m_1 \cdot \ddot{x}_1$. From the "OUT" the values of the suspension stiffness coefficients are sent to the calculation Equations (3), which realizes the normal operation of the suspension (when supplying $c_{Pi} = const$) or failure during overloads and bus traffic on low-quality roads (when supplying $c_{Pi} = c_{Ppri} \to \infty$).

The implemented model in the Matlab Simulink software environment was also checked for adequacy [1]. Data confirming the adequacy of the model were obtained based on the real road tests with the determination of stresses in the investigated element of the base frame [1].

3.2 Comparison of the results of the simulation modelling of the durability of the bus bodies of non-load bearing and frame construction

Simulation modelling of the durability of bus bodies with monocoque and frame construction was carried out at an average speed of 40 km/h and movement on a paved road at maximum permissible passenger load. For comparison, the "Ataman" A092N6 bus with a monocoque body and a maximum permissible number of 52 passengers, and the "Etalon" BAZ-A079 bus with a frame construction and a maximum permissible number of 40 passengers were chosen.

From Table 1, it can be seen that the bus body on a frame chassis has 1.4 times higher durability under the same conditions compared to a body of unibody construction. In addition, during the simulation modelling, a series of values for the durability of the unibody bus body were obtained, which allow us to construct a graphical dependence of the body durability on passenger loading and road type (Figure 4).

In Figure 4, the parameter Y is the durability in units of mileage (km); parameter X_1 is the type of road surface: asphalt concrete (-1), deviation of the microprofile in numerical values is 10 mm; even paving stones (0), deviation of the microprofile in numerical values is 30 mm; low-quality paving stones (1), deviation of the microprofile in numerical values is 50 mm; parameter X_2 is the passenger load: 21 passengers (-1), 52 passengers (0), 83 passengers (1).

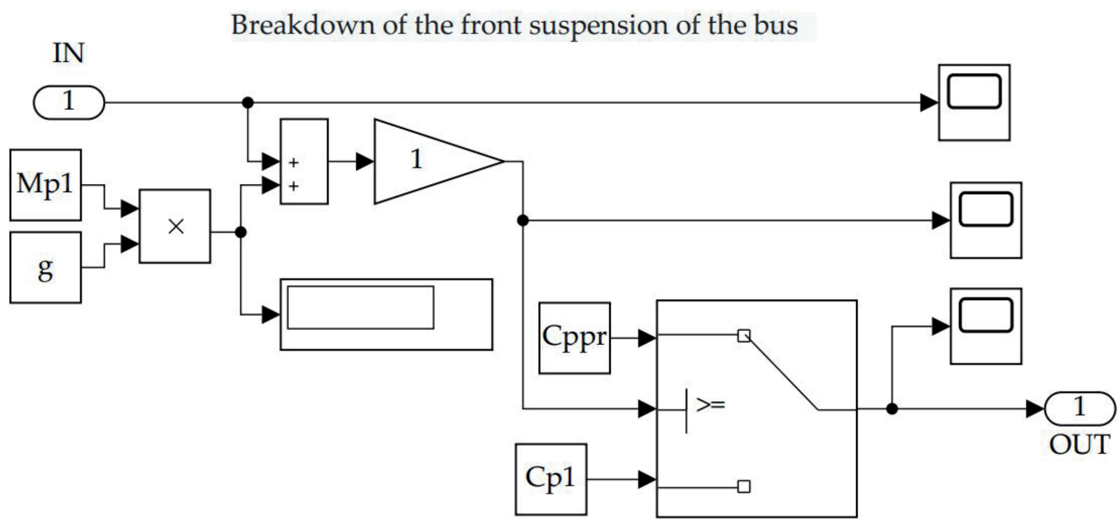

***Figure 3** Implementation scheme of the front suspension breakdown algorithm in the Matlab Simulink software environment*

***Table 1** Comparative assessment of durability of bus bodies of load bearing and frame construction*

Construction of the bus body	Durability of the body frame, km	Durability of the frame (if available), km
Body of load bearing construction	640635	-
Body on frame construction	907653	1452406

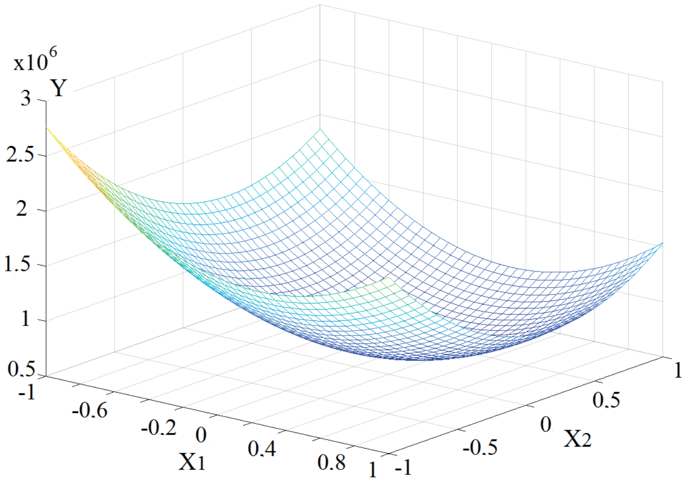

Figure 4 *Dependence of the durability of the bus body with a load of passengers and road type for a non-load-bearing construction*

That is, the X_1 factor corresponding to the limits from -1 to 1 will correspond to the deviation of the road microprofile from 10 mm to 50 mm, and the X_2 factor from -1 to 1 will correspond to the number of passengers from 21 to 83 people.

4 Discussion of the proposed methodology for prognostic assessment of the durability of the bus body in the Matlab Simulink software environment

The proposed methodology for forecasting the body durability of a bus in the Matlab Simulink software environment allows for determining the durability of buses with both non-supporting and frame constructions. The appropriateness of this methodology, and its adequate implementation in the Matlab Simulink software environment, are confirmed by the real experimental trials, as well as by the experience of operating buses with frame and non-supporting body constructions. As a result of simulation modelling, it was established that the durability of a bus body on a frame chassis is 1.4 times greater than that of a non-supporting body. The increased of the durability of the bus body is explained by the fact that the use of a frame provides a more rigid body structure. The frame has a durability that is 2.3 times greater than that of a non-supporting body. Thus, a frame with an increased durability will limit deformation of the body frame during the longer periods of bus operation. This durability of the frame (1452406 km) is explained by the fact that frames are usually made of alloyed steels and are heat-treated. In addition, the frame has an open design, which provides better ventilation and prevents the accumulation of moisture that could cause corrosion. The body frame of a non-supporting construction, which is made of closed-type pipes, contributes to the development of corrosion in closed cavities. Considering that corrosion of internal cavities of the body frame does not practically develop in the first two years (due to the factory protection), it is advisable to treat the internal cavities of pipes every two years. Based on the research results, it could be assumed that a bus body on a frame chassis would be a better option. However, bodies on frame chassis complicate registration/re-registration, repair, and increase the cost of the vehicle kit with a frame by 20 %, as well. The frame also has a number that is entered into registration documents. Over time, the frame number is damaged by corrosion during operation. A heat-treated frame made of alloyed steel under average operating conditions (1452406 km) will require replacement.

The use of simulation modelling compared to high-cost; the long-term durability testing allows for determining the body's durability of a bus under specific operating conditions with minimal expenses in the shortest possible time. The accuracy and maximum approximation to the real operation of simulation modelling is ensured by taking into account the suspension failures of the bus. Unlike [3], which proposes determining the compliance of the body with UN ECE Regulation No. 66 [5] during operation, the prognostic assessment of the bus body's durability in the Matlab Simulink software environment allows predicting the bus body's durability at the design stage. This becomes possible due to the simulation of the influence of the road's microprofile through the wheels and bus suspension on the durability of the body frame (chassis) depending on the material properties, profile section, and corrosion resistance. The proposed methodology allows predicting the durability of the body under different passenger loads, speeds on roads of varying quality, and the intensity of the road treatment with chemical anti-icing agents.

Unlike studies [10-14] that conducted accelerated durability testing using the laboratory stands, the prognostic assessment of the bus body's durability in the Matlab Simulink software environment takes into account corrosion processes that have a significant impact on the bus's durability.

The limitations of this study consist of the fact that the simulation modelling utilized known spectral densities of such types of road surfaces as asphalt, interlocking paving stones, and low-quality paving stones. The properties of the micro-profile of other road surfaces are not applied here. Therefore, to enable research expansion, it is possible to gather micro-profile characteristics of the roads on which a particular bus will operate. Additionally, it is possible to conduct strain gauge measurements of the investigated cross-section on a specific route. However, this option cannot be applied during the design phase, and for operating organizations, this option will be more accurate. In addition, limitations may arise due to the absence of fatigue curve characteristics of new alternative materials for the body or frame structure in reference literature.

The shortcomings of the research include not taking into account the ambient temperature, which could also affect the body's lifespan. There may also be a need for the laboratory durability testing of new body materials, which will increase the cost of research.

The development of this research will involve laboratory durability testing of new body materials and the collection of microprofile of roads of different qualities. As an alternative to roads of different qualities, different known microprofile of roads can be combined in certain proportions to be as close as possible to the actual route.

5 Conclusions

A methodology has been developed for the prognostic assessment of the bus body's durability of the cantilever and frame design, which can be implemented through the transfer function from the road microprofile to the investigated cross-section or by strain gauging the investigated cross-section. The implementation through the transfer function is a universal option and can be used both at the design stage and after production and commissioning. The option using strain gauging of the investigated cross-section will be of interest to operating organizations in specific operating conditions on a real route.

The developed methodology has been implemented by converting the system of equations into a convenient form for solving in the Matlab Simulink software environment. Taking into account the suspension failures allowed for simulation modelling to be closer to the operating conditions when driving on low-quality pavement.

As a result of simulation modelling of the durability of bodies of bearing and frame constructions, it was established that the body of bearing construction has shorter durability by 1.4 times than the body on a frame chassis. The durability of the frame is maximum and 2.3 times greater than the bearing body due to the open and well-ventilated profile made of alloy steel with subsequent heat treatment. The greater durability of the body on the frame chassis is 1.4 times longer than the durability of the bearing body due to its increased rigidity due to the frame.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] RUBAN, D. P. Mathematical model of forecasting durability of bus bodies and checking it for adequacy. *Bulletin of the Vinnytsia Polytechnic Institute* [online]. 2020, **3**(150), p. 81-89. ISSN ISSN 1997-9266, eISSN 1997-9274. Available from: https://doi.org/10.31649/1997-9266-2020-150-3-81-89

[2] RUBAN, D., KRAYNYK, L., RUBAN, H., SOSYK, A., SHCHERBYNA, A., DUDARENKO, O., ARTYUKH, A. Forecasting the durability of public transport bus bodies depending on operating conditions. *Eastern-European Journal of Enterprise Technologies* [online]. 2021, **4**(1(112)), p. 26-33. ISSN 1729-3774, eISSN 1729-4061. Available from: https://doi.org/10.15587/1729-4061.2021.238171

[3] RUBAN, D., KRAYNYK, L., RUBAN, H., HRUBEL, M., DUZHYI, R., BABARYHA, A. Development of technological principles of technical control of bus bodies during operation based on passive safety conditions. *Eastern-European Journal of Enterprise Technologies* [online]. 2022, **6**(1(120)), p. 91-100. ISSN 1729-3774, eISSN 1729-4061. Available from: https://doi.org/10.15587/1729-4061.2022.268178.

[4] FARAHANIA, B. V., RAMOSA, N. V., MOREIRAA P. M. G. P., CUNHAB, R., COSTAB, A., MAIAB, R., RODRIGUES, R. M. Passive safety solutions on transit buses: experimental and numerical analyses. *Procedia*

Structural Integrity [online]. 2022, **37**, p. 668-675. eISSN 2452-3216. Available from: https://doi.org/10.1016/j.prostr.2022.01.136

[5] 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 [online] [accessed 2023-01-16]. 13.03.2011. Available from: http://data.europa.eu/eli/reg/2011/66(2)/oj

[6] AGOSTINACCHIO, M., CIAMPA, D., OLITA, S. The vibrations induced by surface irregularities in road pavements - a Matlab® approach. *European Transport Research Review* [online]. 2014, **6**, p. 267-275. eISSN 1866-8887. Available from: https://doi.org/10.1007/s12544-013-0127-8

[7] NGUYEN, T., LECHNER, B., WONG, Y. D. Response-based methods to measure road surface irregularity: a state-of-the-art review. *European Transport Research Review* [online]. 2019, **11**(43), p. 1-18. eISSN 1866-8887. Available from: https://doi.org/10.1186/s12544-019-0380-6

[8] Corrosion cost and preventive strategies in the United States FHWA-RD-01-156 [online] [accessed 2023-01-16]. Available from: http://www.fhwa.dot.gov/research/publications/

[9] MENEZES SALGADO, R., OHISHI, T., BALLINI, R. A Short-term bus load forecasting system. *International Journal of Computer Information Systems and Industrial Management Applications* [online]. 2011, **3**, p. 336-346. ISSN 2150-7988. Available from: www.mirlabs.net/ijcisim/index.html

[10] CAGRI, I., IZZET, C., ANIL, Y., NAMIK, K., KAROSERI, O. Fatigue life prediction of a bus body structure using CAE tools. In: Fisita 2010 World Automotive Congress: proceedings. Vol. 1. 2010. p. 319-329.

[11] VERROS, G., NATSIAVAS, S. Ride dynamics of nonlinear vehicle models using component mode synthesis. *Journal of Vibration and Acoustics* [online]. 2002, **124**(3), p. 427-434. ISSN 1048-9002, eISSN 1528-8927. Available from: https://doi.org/10.1115/1.1473828

[12] PAPALUKOPOULOS, C., NATSIAVAS, S. Dynamics of large scale mechanical models using multi-level substructuring. *Journal of Computational and Nonlinear Dynamics* [online]. 2007, **2**(1), p. 40-51. ISSN 1555-1415, eISSN 1555-1423. Available from: https://doi.org/10.1115/1.2389043

[13] YU, F., GUAN, X., ZHANG, J. Modelling and performance analysis for a city low-floor bus based on a non-linear rigid elastic coupling multibody model. *SAE Technical Paper* [online]. 2002, 2002-01-3094. ISSN 0148-7191, eISSN 2688-3627. Available from: https://doi.org/10.4271/2002-01-3094

[14] KRISHNAMOORTHY, M., SAM PAUL ALBERT, M. Durability analysis of a vehicle by virtual test model (VTM). Ashok Leyland Ltd., Chennai, India [online] [accessed 2023-01-29]. 2014. Available from: https://www.techbriefs.com/component/content/article/tb/pub/techbriefs/test-and-measurement/19542

[15] Dassault Systems Matlab Corporation [online] [accessed 2023-01-21]. 2020. Available from: https://www.matlab.com/

[16] SILAEV, A. Spectral theory of suspension of transport vehicles / Spektralnaya teoriya podressorivaniya transportnyh mashin (in Russian). Moscow: Mechanical Engineering, 1972.

[17] RAIKHER, V. Spectral summation hypothesis and its application to the determination of fatigue life under the action of random loads. Reliability problems in structural mechanics / Gipoteza spektralnogo summirovaniya i eyo primenenie k opredeleniyu ustalostnoj dolgovechnosti pri dejstvii sluchajnyh zagruzok. Problemy nadezhnosti v stroitelnoj mehanike (in Russian). Vilnius, 1968.