

This paper addresses the issue related to forecasting the durability indicators of public transport buses under operational conditions. It has been established that when buses are operated to transport passengers the bus bodies wear at different intensities. During operation, the strength of the body frame weakens under the influence of corrosion in combination with sites of fatigue destruction. As it was established, the intensity of corrosion of the bus body depends on the number of residents in the city where the bus is operated. The earlier established dependences were taken into consideration; the current study has identified two conditional variants of corrosion evolution based on the number of inhabitants: up to 1 million and exceeding 1 million. The expediency of repairs and their impact on the bus passive safety has been analyzed. It was found that the elements of the body frame, without external characteristic damage, no longer meet the specified conditions of strength as a result of sign-alternating loads and during long-term operation.

Determining the durability of the bus body was made possible through the construction of a mathematical model. The model's adequacy was confirmed by road tests of the bus. The devised model describes the movement of the bus over a road surface with different micro profiles, with different corrosion penetration, different loading by passengers, and bus speeds.

It was established that the reason for the evolution of structural corrosion is the influence of salt mixtures preventing the icing of roads, as well as ignoring the washing of buses after such trips.

It is recommended to use new software for the in-depth study into this issue addressing the combination of various factors of destruction: cyclic loads at variable bus speeds and the corrosion progress. The study results could make it possible to predict a life cycle of the body frame under factors that correspond to actual operating conditions

Keywords: bus operation, durability modeling, body frame, body corrosion, fatigue strength

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FORECASTING THE DURABILITY OF PUBLIC TRANSPORT BUS BODIES DEPENDING ON OPERATING CONDITIONS

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1. Introduction

The bus is designed in accordance with the technical specifications. Accordingly, the specified passenger capacity, overall dimensions, maximum speed, type, engine power, etc. are provided. In addition, one of the important parameters is passive bus safety. Passive safety control in line with UNECE Rules No. 66 [1] is tested by overturning the bus and determining the geometric dimensions of the deformation of the formed sloping body plane. After carrying out all measures to check the bus for compliance with the Rules, requirements, and other standards, certificates for compliance are obtained.

That gives grounds for the serial production of buses and sale to consumers through a dealer network. Thus, the new model begins operation. At the same time, the durability of the bus is unknown. In the case when engine assemblies from other buses or trucks are installed on buses, the resource of these units can still be predicted. However, the body resource cannot be determined since full-time pre-series resource tests are not carried out in this country due to significant costs. When operating the bus for ten years (the mileage averages about 1 million km), one can acquire statistics on the resource of both individual units and the bus in general. However, the task to obtain the bus's resource indicators before commissioning

remains relevant. Thus, there is a need to devise methods and tools for predicting the durability of the body frame, as well as checking its compliance with passive safety in line with the UNECE Regulations No. 66.

2. Literature review and problem statement

When overturning a bus, the UNECE Regulations No. 66 [1] define if the bus complies with passive safety requirements. However, at the design stage, it is advisable to carry out simulations, which is much cheaper than the destruction of a new bus. Work [2] shows that proper maintenance of the bus body ensures long-term and reliable operation of the bus in general. However, the cited work does not indicate that timely detection of corrosion and fatigue destruction sites could also improve the durability of the bus body. Paper [3] notes that during operation, as a result of corrosion and sign-alternating loads, the strength of the body frame elements deteriorates, which is confirmed by the experimental studies of cut samples from body frame elements at a breaking machine [3]. After 5–9 years of bus operation, structural corrosion makes it impossible to further operate it, so such buses need restoration repairs. It has been proven in [4] that losses from corrosion damage significantly reduce the efficiency of bus transportation. Therefore, during the simulation of the durability of bus bodies, it is necessary to take into consideration the intensity of corrosion of body frame elements. The authors of [5] proposed the use of stainless steel in bus structures, which could significantly improve durability. However, the application of stainless steel increases the weight of buses and their cost.

It is confirmed in [6] that the operation of buses is accompanied by constant overloads, leading to premature damage to body frame elements and suspension elements, especially when transporting passengers in low-entry public transport buses. Despite the above-specified shortcomings of low-floor structures, buses of this type have become widespread and convenient for the transportation of public transport passengers [7, 8]. Therefore, the issue of determining the durability of public transport bus bodies is relevant for a significant proportion of carriers and manufacturers. Quite often, there are damages to the body frame, which cannot be detected without special equipment. As shown by laboratory tests [9], conducted according to the methodology reported in [10], the following was established. Elements of the body frame, which are not externally damaged, when viewed under an electron microscope, have a significant number of fatigue cracks and a violation of the structure of the material [11]. Therefore, study [9] confirms the feasibility of devising new procedures for assessing the durability of bus bodies that best meet actual operating conditions. To predict the durability of the body frame, a methodology for assessing the durability of body frame elements under operational conditions [11] was developed. The devised procedure implies taking into consideration the speed of the bus, the quality of the road surface (a road's micro profile), loading by passengers, and corrosion intensity [11]. There is also a methodology for predicting the loading of buses by passengers [12] but it does not make it possible to determine the durability of buses as close as possible to the actual operation. Based on the procedure reported in [11], a mathematical model was built, which describes the transfer of effort from the micro profile of a road to the examined element of the body frame [13]. The model given in [13] takes into consideration, similarly to the model

reported in [14], the forces transmitted from the road micro profile but the model from [13] also takes into consideration the corrosion of the bus body frame, which corresponds to actual operating conditions. The corrosion processes of the bus body are described in [15], considering [16], and according to dependences [8], derived from treating the statistics on bus operation in cities with different numbers of inhabitants. Combining works [8, 15, 16] has made it possible to mathematically describe the corrosion processes of bus bodies, taking into consideration the evolution of atmospheric corrosion and corrosion under the influence of aggressive chemicals preventing the icing of roads, especially in large cities.

Salt-sand mixtures are used to combat icing, including highly effective magnesium chloride-based products that create favorable conditions for the development of corrosion [17]. Given such operation, the timely regular washing of buses reduces the aggressive effect of salt-sand mixtures on the body [18]. Paper [19] describes measures to reduce the impact of aggressive environments on car bodies. These measures are also relevant for public transport buses. Work [20] proves the effectiveness of corrosion protection using school buses as an example. Thus, in determining the durability of bus bodies, the simulation would make it possible to assess the impact of maintenance quality on corrosion.

The devised model also considers loading with passengers from the rated values to one-and-a-half-time overload. The built model is implemented in the MATLAB Simulink 2017 b programming environment [21]. To confirm the adequacy of the model, road tests of the Ukrainian-made bus A09216, based on the Japanese assembly units, were carried out [22], which confirmed the obtained values of deformations in the examined body frame element [13]. The adequacy of a given model was also confirmed when predicting the resource of the most loaded elements of the body frame. The results were compared with statistics for constant bus overload when driving on low-quality roads, at an average speed of 40 km/h [13]. That makes it possible to conduct further research on determining the durability of bus bodies.

Based on the review of studies on determining the life cycle of buses, it was found that there is practically no information in the field of automotive engineering on determining the durability of bus bodies. Determining the durability of railroad cars, and water and air transport vehicles [23], is mainly considered. Our review of scientific studies reported in [24–28] has established that the bus durability modeling was indeed carried out but no corrosion and actual road conditions were taken into consideration. Modeling was performed under conditions corresponding to the modes of accelerated durability tests at the laboratory bench. However, such accelerated tests do not take into consideration the simultaneous impact of corrosion and fatigue destruction of body frame elements. Work [29] describes the forecasting of the durability of the suspension lever of a passenger car, which may also be relevant in predicting the durability of the bus body frame elements. However, that model [29] also does not take into consideration the corrosion destruction of the part under study. Full-time tests of buses for strength and durability are indeed carried out [30–32] but this method requires significant material costs.

3. The aim and objectives of the study

The purpose of this work is to determine the durability of the elements of the body frame under operational conditions.

To accomplish the aim, the following tasks have been set:
 – to conduct experiments using a simulation model by changing the predefined parameters of bus durability under the selected conditions;
 – to derive mathematical dependences of the estimated mileage of the bus before the onset of the limit condition of its body operation, based on the research planning matrix.

4. The study materials and methods

To study the impact of operational factors on the durability of the body frame, the MATLAB 2017 b programming environment was selected, which makes it possible to carry out simulation modeling. The Simulink application (USA) enables solving a system of equations describing a bus as a dynamic system.

4.1. Selecting the range of change in the examined factors

The input parameters are a micro profile of three types of road: asphalt pavement, flat paving stones, low quality paving stones. At the same time, the empirical dependences derived by NAMI specialists during the research on roads with the corresponding micro profiles [33] are used. The values of spectral density $\rho(l)$ [34], which are applied to simulate the effect of the road micro profile on the suspension of the car, passengers [35], and the vehicle in general [34, 36, 37], were used in modeling the durability of bus bodies; they are given in Table 1.

Table 1

Values of spectral density for roads' micro profiles [34]

Road surface type	Estimation equation
Asphalt pavement micro profile	$\rho(l) = 0.85e^{-0.2l} + 0.15e^{-0.03l} \cdot \cos 0.6l$
Flat paving stones micro profile	$\rho(l) = e^{-0.45l}$
Low-quality paving stones micro profile	$\rho(l) = 0.85e^{-0.5l} + 0.15e^{-0.2l} \cdot \cos 2l$

Spectral density $\rho(l)$ describes the type of a road surface and makes it possible to determine specific values for the micro profiles of the selected road types.

When modeling in MATLAB Simulink, specific values for a micro profile time variable must be submitted to the input system of equations. To this end, we use a procedure from [38], which implies deriving the specific values for a road's micro profile from the time function.

The numerical specific values for the road's micro profile X_1 , according to [38], are determined from the following dependence:

$$x(t) = \zeta(t) \times \left[\frac{A_1 \cdot \sqrt{2 \cdot \sigma_x^2 \cdot \alpha_1 / h}}{s + \alpha_1} + \frac{A_2 \cdot \sqrt{2 \cdot \sigma_x^2 \cdot \alpha_2 / h} \cdot s + A_2 \cdot \sqrt{2 \cdot \sigma_x^2 \cdot \alpha_2 / h} \cdot \sqrt{\alpha_2^2 + \beta_2^2}}{s^2 + 2 \cdot \alpha_2 \cdot s + \alpha_2^2 + \beta_2^2} \right], \quad (1)$$

where $\zeta(t)$ is the discrete white noise; h is the integration step; s is the differentiation operator.

Based on dependence (2), the MATLAB Simulink implemented the following subsystem [38] (Fig. 1).

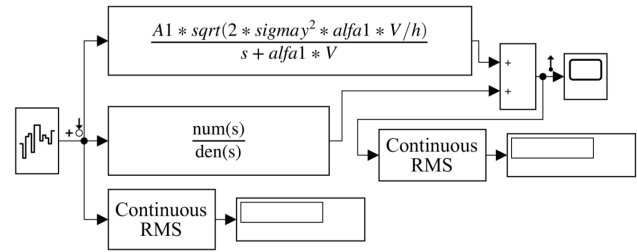


Fig. 1. Subsystem for calculating the values of a road's micro profile by the time function

The coefficients corresponding to a particular road micro profile are entered in the MATLAB workspace.

In addition, the devised model involves the processing of specific numerical data acquired during the study of the road surface. Such values can be entered into the workspace as a matrix, by using the call function and submit specific values of the road's micro profile to the system.

In addition, the input parameters are the number of passengers: seated passengers only; the maximum number of passengers; 1.5 times the number of passengers exceeding the permissible number. For the *Ataman* bus A092N6, made in Ukraine based on the Japanese assembly units, those numbers are 21, 52, and 83 passengers. The corrosion of the base frame would be affected by the service life and, accordingly, mileage, as well as the city where the bus is operated. In a city with a population of up to 1 million, there would be a lower corrosion intensity [13] than that where there are more than 1 million people, by about 2 times.

A given model makes it possible to treat the experimentally derived relative deformations of any element in the body frame according to the devised procedure [22]. Relative deformations ϵ are converted into stresses σ in line with the Hook's law:

$$\sigma = E \cdot \epsilon, \quad (2)$$

where E is the Young modulus (for steel 20: $E = 2.12 \times 10^5$ MPa [22]); ϵ is the relative deformation, derived during the research.

Thus, values for stresses σ can be obtained in two ways: estimated and experimental. The estimation method for determining stresses in the studied element should be used at the bus design stage while the experimental one can be recommended to operator organizations for a more accurate determination of durability corresponding to actual routes. With the experimental method, it is possible to conduct road tests of the bus along a specific route with actual passenger traffic during the daily (weekly, annual) cycle of passenger transportation. Based on the acquired data, it is possible to model the durability of body frame elements under detailed conditions. Spectral density is determined from the derived values of σ stresses during modeling.

The durability of the bus body frame (s) is calculated using the Reicher formula [39]:

$$t = \frac{2 \cdot \pi \cdot A}{\Delta^{m_N} \cdot (\sqrt{2})^{m_N} \cdot \Gamma\left(\frac{m_N + 2}{2}\right) \cdot \left(\int_0^{\frac{m_N}{2}} S_0(\omega) \cdot \omega^{m_N} d\omega\right)^{\frac{m_N}{2}}}, \quad (3)$$

where $\Delta = \sqrt{D}$ is the standard deviation of current stress values; D – variance; $S_0(\omega) = S(\omega) / D$ – reduced spectral

density; $\Gamma\left(\frac{m+2}{2}\right)$ – gamma-function; A and m_N are the characteristics of the durability curve ($A = N \cdot \sigma_a^{m_N}$).

Next, we determine the mileage (in km) until the destruction of a body frame element, which corresponds to the life cycle limit:

$$L = V \cdot t, \tag{4}$$

where V is the mean bus movement speed.

As statistics on bus traffic show, the average speed V in the city is 40 km/h.

The mathematical model is described in detail in paper [13]. A given model works as follows. Input parameters form the value of accelerations of the examined cross-section. Newton's second law determines the magnitude of the effort in the cross-section. Then, according to the known effort and size of the cross-section area, the stress in the studied cross-section is determined. Corrosion is taken into consideration, which leads to a decrease in the thickness of the walls of the frame tubes, and, as a result, the area of the cross-section is reduced. In this way, stress would increase with other unchanging parameters. The model also took into consideration possible suspension breakdowns caused by overloads and bus traffic over low-quality roads. In the model, a road of low quality denotes paving stones with depressions and hills. The modeling took into consideration the movement of the bus at increased speeds (40 km/h is enough for overload). Suspension breakdown occurs when the product of acceleration \ddot{X}_i of non-sprung mass on this mass m_{npi} plus the distributed value of the weight of the sprung mass M_{pi} is greater than the product of the elasticity coefficient k_i of the suspension by the run of the breakdown suspension X_{maxi} :

$$m_{npi} \cdot \ddot{X}_i + M_{pi} > k_i \cdot X_{maxi}. \tag{5}$$

Thus, during the breakdown, the non-sprung masses move with the sprung masses as one unit while the rigidity of the suspension tends to infinity.

4. 2. Substantiating and building a matrix of the simulation modeling

To build an empirical dependence of the impact of a road's micro profile (X_1) and loading with passengers (X_2) on durability (Y_i), a full factor experiment (FFE 2^2) was carried out [40]. Table 2 gives the selected factors and their levels (upper: +1; lower: -1; basic: 0).

Table 2

The value of the factors and their levels, respectively

Factor		Basic level	Lower level (-1)	Upper level (+1)
Road's micro profile, mm	X_1	Flat paving stones micro profile	Asphalt pavement micro profile	Low-quality paving stones micro profile
		30	10	50
Passenger load, people	X_2	52	21	83

The number of experiments is determined from the following formula: $N = 2^2 = 4$. The planning matrix of the experiment is summarized in Table 3.

Table 3

Experiment planning matrix

Experiment number	X_1	X_2	Y_i
1	-1	-1	Y_1
2	+1	-1	Y_2
3	-1	+1	Y_3
4	+1	+1	Y_4
1_0	0	0	Y_{01}
2_0	0	0	Y_{02}
3_0	0	0	Y_{03}

Y_i – the durability of a body frame is the mileage L (determined from formula (4) during modeling in km) until the destruction of a body frame element, which corresponds to the life cycle limit.

An equation of the mathematical model in a natural scale takes the following form:

$$Y = b_0 + b_1 \cdot X_1 + b_2 \cdot X_2 + b_{12} \cdot X_1 \cdot X_2. \tag{6}$$

To proceed from the natural to normalized scale, we encode the X_1, X_2 values using the following formulas:

$$X_i = \frac{\tilde{X}_i - \tilde{X}_{i0}}{\Delta\tilde{X}_i}, \tag{7}$$

where X_1 is the encoded value of the factor (normalized); i – factor number; \tilde{X}_i is the current value of the factor (on a natural scale); \tilde{X}_{i0} is the value of the factor at the basic level (in natural scale); $\Delta\tilde{X}_i$ is the factor variation interval (on a natural scale), calculated from the following formula:

$$\Delta\tilde{X}_i = \frac{\Delta\tilde{X}_{i\max} - \Delta\tilde{X}_{i\min}}{2}, \tag{8}$$

where $\Delta\tilde{X}_{i\max}$ is the value of the upper level of the factor; $\Delta\tilde{X}_{i\min}$ is the lower level value of the factor.

The equation of the mathematical model at a normal scale takes the following form:

$$\hat{Y} = b_0 + b_1X_1 + b_2X_2 + b_{12}X_1X_2. \tag{9}$$

At the same time, the factors are dimensionless; their values are taken as follows: (+1) – the upper level, (-1) – the lower level, and (0) – the average (basic) level.

To calculate the regression coefficients, a least-square method (LSM) was used. The LSM condition is written as follows:

$$U = \sum_{i=1}^N \xi_i^2 = \min. \tag{10}$$

Formulas for calculating regression coefficients can be written in the following form:

$$b_0 = \frac{1}{N} \sum_{i=1}^N y_i; \quad b_j = \frac{1}{N} \sum_{i=1}^N y_i X_{ji}; \quad b_{ij} = \frac{1}{N} \sum_{i=1}^N y_i X_{ii} X_{ji}, \tag{11}$$

where N is the total number of experiments; y_i is the response parameter at the i -th point; X is the encoded value of the factor;

i – the number of the experiment (a line in the planning matrix); $j = u = 0, 1, 2, \dots, k$ are the factor numbers.

The variance of the repeatability of experiments is determined from the following formula:

$$S_0^2 = \frac{1}{n-1} \sum_{q=1}^n (y_q - \bar{y})^2, \tag{12}$$

where n is the number of repeated experiments; y_q is the response parameter; \bar{y} is the arithmetic mean deviation of the response parameter:

$$\bar{y} = \frac{1}{n} \sum_{q=1}^n y_q, \tag{13}$$

where $q = 1, 2, \dots, n$ is the number of the parallel experiment.

The regression coefficients were checked by pre-defining the confidence interval of the coefficients. For all regression coefficients, confidence intervals are equal; they are determined from the following formula:

$$\Delta b_j = \pm t \sqrt{\frac{S_0^2}{N}}, \tag{14}$$

where t is the tabular value of the Student criterion at the assigned level of significance α and the corresponding number of degrees of freedom. The level of significance was taken as $\alpha = 5\%$ [40].

The number of degrees of freedom for repeatability variance is determined from the following formula:

$$f_1 = n - 1, \tag{15}$$

where n is the number of repeated experiments; 1 is the number of degrees of freedom used in calculating the arithmetic mean for the response parameter.

The regression coefficient is significant if its absolute value is greater than the confidence interval.

The model adequacy check was carried out according to Fisher's F -criterion:

$$F = \frac{S_{ad}^2}{S_0^2}, \tag{16}$$

where S_{ad}^2 is the adequacy variance,

$$S_{ad}^2 = \frac{\sum_{i=1}^N (y_i - \bar{y})^2}{f_2}, \tag{17}$$

where f_2 is the number of degrees of freedom for the adequacy variance, equal to the number of different experiments whose results are used in calculating regression coefficients, minus the number of coefficients determined;

$$f_2 = N - (k + 1), \tag{18}$$

where N is the total number of experiments; k – the number of factors in the experiment.

The level of significance, similar to the previous case, is adopted $\alpha = 5\%$. The model can be considered adequate if the estimated value of the Fisher's F criterion does not exceed a tabular value.

5. The results of studying the durability of public transport bus bodies during operation

5.1. The results of modeling the parameters of bus durability under the selected conditions

Based on the designed plan of the experiment, we simulated the durability of the bus body and derived the values for durability given in Table 4.

Table 4

Results of durability simulation based on the planning matrix of the experiment

Experiment number	X_1	X_2	Y_i
1	Asphalt concrete pavement micro profile	21 passengers	1,289,315 km
2	Low-quality paving stones micro profile	21 passengers	457,232 km
3	Asphalt concrete pavement micro profile	83 passengers	756,321 km
4	Low-quality paving stones micro profile	83 passengers	57,523 km
5	Flat paving stones micro profile	52 passengers	640,635 km
6	Flat paving stones micro profile	52 passengers	670,738 km
7	Flat paving stones micro profile	52 passengers	680,737 km

Based on the data in Table 4, we calculated the mathematical dependences of bus durability.

5.2. The results of calculating the mathematical dependences of bus durability

Based on the above algorithm, a program was developed to calculate the regression coefficients for the built mathematical models on a normal and natural scale, as well as to perform a check on the adequacy of the mathematical models obtained. The general view of the software interface is shown in Fig. 2. The program was developed using Microsoft Excel software.

The result of our calculations is the following approximating polynomial:

$$\hat{Y} = 640,097.8 - 382,720.25X_1 - 233,175.75X_2 + 33,321.25X_1X_2. \tag{19}$$

The significance of regression coefficients is calculated taking into consideration the value of the confidence interval Δb_j . According to the calculation results, we can conclude that at $\Delta b_j = 40,165.8$ all calculated regression coefficients, except b_{12} , are significant.

The resulting mathematical models are adequate because, according to the calculation of the value of the F -criterion by Fisher, they equal $F_c = 5.096$, which is much less than the tabular value $F_t = 19$ [40].

	A	B	C	D	E	F	G	H
1	The factor level	X1 (The microprofile of the road, mm)	X2 (The passenger load, people)	LnRa	LnP		The calculation of the mathematical model of bus durability A092H6	
2	1	50	83	1,698970004	1,91907809			
3	-1	10	21	1	1,32221929			
4	0	30	52	1,477121255	1,71600334			
5								
6								
7	№	X0	The microprofile of the road	The passenger load	X12	L, km	ln(L)	LN(L)
8	1	1	1	1	1	57523	4,75984153	24201,75
9	2	1	1	-1	-1	457232	5,66013662	490553,25
10	3	1	-1	1	-1	756321	5,87870616	789642,25
11	4	1	-1	-1	1	1289315	6,11035904	1255993,75
12	5	0	0	0		640635	5,80661066	
13	6	0	0	0		670738	5,82655291	
14	7	0	0	0		680737	5,83297936	
15								
16								
17	b0	b1	b2	b12				
18	640098	-382720,25	-233175,75	33321,25				
19	The assessment of significance of the coefficients							
20	1	1	1	0	The linearity of the mode		linear	
21	The coefficient for the equation with real numbers							
22	5467371	-1913601,25	-1165878,75	0				
23								
24	The variance of the experiment reproducibility:				435723502			
25	The number of degrees of freedom 1:				2			
26	The variance of the regression coefficients:				87144700,5			
27	The tabular criterion of the Student for p=0,95:				4,30265273			
28	The confidence interval of the regression coefficients:				40165,8337			
29								
30	The number of degrees of freedom 2:				2			
31	The adequacy variance:				2220611403			
32	The calculation criterion of the Fisher for p=0,95:				5,09637738			
33	The tabular criterion of the Fisher for p=0,95:				19			
34	The model adequacy:				adequate			

Fig. 2. General view of the software interface for calculating regression coefficients and checking the resulting mathematical model for adequacy

6. Discussion of results of studying the durability of public transport bus bodies during operation

The result of our experiments involving a simulation model is the derived ultimate mileage of the bus body, which is limited to the destruction of body frame elements and predetermines its durability. As the simulation results show (Table 4), the minimum value of durability would be reached at one and a half times overload (83 passengers) and when driving on a low-quality road (low-quality paving stones micro profile); it is only 57,523 km of mileage. Such a small resource of the bus (durability) is explained by excessive loads on the body frame elements from the low-quality road, on the one hand, and from overload with passengers, on the other hand. Such results are commensurate with the operation of buses on actual routes on low-quality roads. The maximum closeness of our results to actual operation can be explained by the fact that the mathematical model of bus movement takes into consideration suspension breakdowns. Table 4 demonstrates that with one and a half times the bus capacity (83 passengers) and movement on the road of high quality, the durability of the bus body is 756,321 km. And such an indicator of durability almost corresponds to the life cycle of the power unit (the manufacturer of the assembly units declares a resource of about 1 million km). This value of durability (756,321 km) with one and a half times overload is explained by a structurally predefined coefficient of body strength, which is 1.75.

Simulation results make it possible to estimate the durability of a bus body as close as possible. Unlike [23], which considers the assessment of the durability of railroad cars, where the sign-alternating loads from the micro profile of the road were not taken into consideration since the

wheels of cars move over steel tracks for which taking into consideration the micro profile of the road is impractical. In works [24–28], which modeled the durability of buses, and which did not take into consideration body corrosion, the results were somewhat idealized. Therefore, unlike [24–28], the approximation of modeling results became possible by taking into consideration corrosion processes in combination with traffic on roads of different quality and different loading with passengers. Unlike the full-time tests for durability reported in [30–32], the proposed and implemented methodology makes it possible to determine the durability of the bus body at minimal cost in the shortest possible time.

Thus, the resulting solutions enable determining the durability of a body frame taking into consideration the micro profile of a road of different quality (also considering suspension breakdowns), taking into account the different loadings with passengers, in combination with the corrosion of the bus body, which were not previously used to determine the durability of buses.

The limitations of this study are as follows. A given mathematical model can be used without changes to study the durability of the buses A092N6 «Ataman» under different operating conditions. The methodology makes it possible to apply a given model to other public transport buses only when entering the parameters of buses to be investigated with a follow-up check of the adequacy of the model. A given model cannot be applied without significant changes for buses not involved in public transportation.

The caveat of the current study is that the simulation was carried out at a steady average speed of 40 km/h and on the specific fixed micro profiles of the road surface. In actual operation, a bus running along one route can move over roads with sections of various types of micro profiles: asphalt concrete

pavement, paving stones of satisfactory quality, paving stones with depressions and hills; our work investigated traffic only on the road with the same type of surface. In this case, it would be advisable, with further research, to take into consideration the percentage of bus traffic on roads of different quality. Modeling would be more exact if there is an issue with operating organizations to determine the durability based on the results from measuring the characteristics of the micro profile of a road involving the acquisition of an array of data. Entering an array is already provided for in the developed model.

During further research, it is also possible to measure the strains in the most loaded elements of the body frame and determine their deformations on actual routes. That could make it possible to acquire an array of data that can be added to the model at the stage of calculating stresses in the elements of the body frame and take into consideration the actual micro profile of the road, loading with passengers, and changing the speed of movement.

7. Conclusions

1. We have simulated bus durability parameters under selected conditions and established that the durability of the bus body is significantly influenced by bus suspension breakdowns, with serviceable suspension, and when driving on low-quality roads, as well as constant overloads. Moreover, taking into consideration the breakdowns of bus suspensions has brought the modeling results as close as possible to actual operation. The minimum mileage until the destruction of the long-body frame of the bus base was 57,523 km, with one and a half times the overload with passengers, and the movement

of the bus along the pavement of low quality. The maximum mileage until the destruction of the beam frame of the bus body base was 1,289.315 km when overloading with only seated passengers, and the movement of the bus on a high-quality road with asphalt concrete pavement. Therefore, the durability of the bus body of public transport, with such a structure, is within 57,523–1,289.315 km depending on the operating conditions. Thus, by changing the structure of the body, one can affect the durability at the design stage, thereby deriving specific values for the durability of the bus body.

2. The equation of the mathematical model on a normal scale has been built:

$$\hat{Y} = 640,097.8 - 382,720.25X_1 - 233,175.75X_2 + 33,321.25X_1X_2,$$

which makes it possible to predict the failure-free operation of the bus body frames, which were compared to actual operating conditions. Our results would allow the scientists and design engineers to carry out an in-depth study of this issue by combining various factors of destruction such as the cyclic sign-alternating loads on the elements of the body frame at variable speeds of bus movement and the evolution of atmospheric and salt corrosion. The adequacy has been confirmed by the Fisher criterion ($F_c < F_t$). The absolute maximum value is accepted by the coefficient b_1 , so the factor X_1 (road micro profile) has a greater impact on the durability of the bus body, which is confirmed by the increased durability of the body in the experiment involving an asphalt concrete pavement when loading 83 passengers (durability, 756,321 km), compared to the experiment involving flat paving stones when loading 52 passengers (durability, 640,635 km).

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