UDC 629.113
DOI: 10.15587/1729-4061.2022.268178

DEVELOPMENT OF TECHNOLOGICAL PRINCIPLES OF TECHNICAL CONTROL OF BUS BODIES DURING OPERATION BASED ON PASSIVE SAFETY CONDITIONS

Dmytro Ruban
Corresponding author
PhD, Associate Professor*
E-mail: ruban_dimon@ukr.net
Lubomyr Kraynyk
Doctor of Technical Sciences, Professor*
Hanna Ruban
Teacher
Department of Fundamental Disciplines
Tcherkasy State Business-College
V. Chornovola str., 243, Cherkasy, Ukraine, 18028
Mykhailo Hrubel
Doctor of Technical Sciences, Associate Professor
Department of Cars and Vehicles Fleet Engineering
Hetman Petro Sahaidachnyi National Army Academy
Heroiv Maidanu str., 32, Lviv, Ukraine, 79026
Roman Duzhyi
Deputy Head of the Center, Head of Department
Department of Innovative Technologies Implementation and Technical Support of the Educational Process**
Andrii Babaryha
Senior Researcher
Department of Analysis and Generalization of Information**
*Department of Automobiles and Tractors
Lviv National University of Environmental Management
V. Velikoho str., 1, Dublyany, Ukraine, 80381
**Multinational Staff Officer Training and Research Centre
The National Defence University of Ukraine named after Ivan Cherniakhovskyi
Povitroflotskyi ave., 28, Kyiv, Ukraine, 03049

The object of this study is the permissible limits of aging of bus bodies during operation and the formation of appropriate recommendations to control them based on the conditions of compliance of the body with passive safety rules.

According to the current method, the new model of the bus is checked for compliance with passive safety by a destructive method. However, during operation, the physical and mechanical properties of the body deteriorate until the moment of non-compliance with the requirements of passive safety. Therefore, the principles of technical control of bus bodies under the conditions of passive safety by non-destructive methods, the implementation of which became possible during the operation of buses, have been developed. 3 implementation options have been proposed.

In the first variant, visual control is complemented by a measuring tool – an ultrasonic thickness gauge for measuring the thickness of the frame pipes. This method has not previously been used in the certification of vehicles.

The second option involves checking the mechanical properties during repairs on a breaking machine. It is proved that during the restoration repairs of buses, the endurance limit of the steel elements of the body frame is reduced by 1.14–3.33 times.

In the third variant, the methodology for modeling and calculating the stressed-strained state of the body was improved based on the method of finite elements, taking into account the effects of corrosion and fatigue strength of the metal of the frame. When modeling, the deformation of the body racks exceeded the permissible values by 1.5–2.0 times. This non-destructive method makes it possible to check the bus for compliance with passive safety requirements during operation, which was previously impossible.

The scope of practical application is the introduction of research results into the real practice of operating buses at the legislative level.

The results are suitable for monitoring the technical condition of buses by non-destructive methods during operation

Keywords: bus operation, bus body, passive safety, non-destructive testing

Received date 13.09.2022
Accepted date 15.11.2022
Published date 30.12.2022

How to Cite: *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*

1. Introduction

The main condition for the industrial production of a new model of the bus is checking it for compliance with the passive safety of passenger transportation in accordance with the Rules of the United Nations Economic Commission for Europe (UNECE) No. 66 [1]. Therefore, in real production, the bus is designed with a initially manufactured prototype.

To confirm compliance with the Passive Safety Rules, the bus body is destroyed when tipped to the side. This makes it possible to assess the degree of deformation of the cabin racks, which limits the living space of passengers. Comparing the results of such an experiment with the permissible values, it is concluded that the bus complies with UNECE Rules No. 66. The bus, which has been certified in full, is then produced industrially. And after that, the check for compliance of the bus with passive safety is never performed again. The buses are then sold through a dealer network and start operating. During operation, the material properties of the bus body are constantly deteriorating. The deterioration in the properties of bus bodies is caused by passenger loading, unevenness of the road surface, and corrosion. As experience shows, during peak hours there is a one and a half times overload with passengers. Buses can move on low quality roads (potholes, humps, poor quality paving stones). Corrosion can be caused by atmospheric influences and aggressive anti-icing agents of roads. The speed of the bus has a direct impact on reducing the durability of the body, especially on low-quality roads. Thus, inevitably, there will come a moment of inconsistency of body strength with UNECE Rules No. 66. As a rule, buses undergo periodic technical control [2] but this is limited to visual inspection and does not imply complete removal of the bus body and its non-admission to further operation. In Germany and other European countries, the comprehensive control system Technischer Überwachungsverein (TÜV) is used [3]. Such control [3] visually determines the presence of corrosion, cracks in the body frame, and other damage. According to TÜV, based on the results of auditing, there are four options for the conclusions of such an inspection. The first is admission to the transportation of passengers and obtaining a certificate. The second is permission to operate without passengers. The third is the prohibition of operation until the elimination of the detected deficiencies with repeated certification. The fourth is a complete ban on operation with subsequent disposal of the bus. A complete ban on the operation of the bus involves the presence of deep corrosion and cracks in the non-bearing elements of the body frame. This condition of the body does not allow for high-quality repairs. Full restoration of the body will be achieved either when it is replaced with a new one or when cutting out all damaged elements. As the inspection of the abandoned bodies shows, all elements, at least below the windowsill, should be replaced. And this requires significant material costs, which, according to German experts, is irrational. Despite this approach of German specialists, TÜV does not provide for an assessment of compliance with passive safety rules during operation. Unlike the German TÜV, bus bodies with critical cracks and corrosion damage can be treated without restrictions on repairs. With such repair, elements are replaced only with external signs of damage. However, the material properties of other elements that outwardly do not have damage during operation also degrade. As a result of such repairs, it is impossible to achieve proper indicators of compliance with the conditions of passive safety of passenger transportation.

Scientific research on this topic is important because it will make it possible to identify the moment of occurrence of non-compliance of the bus body with the requirements of UNECE Regulation No. 66 on passive safety. The results of such studies are needed in real practice because non-destructive control methods make it possible to check the compliance of the bus body with UNECE Rules No. 66 during operation. In case of a positive conclusion based on the results of such non-destructive testing, the body will not be removed and the bus immediately returns to the route to transport passengers.

2. Literature review and problem statement

In [4], the results of the assessment of the passive safety of the bus body of the frame structure during operation are given. However, this assessment is in no way related to the technical control of bus bodies during operation. That study requires expanding the experimental base and obtaining more options for the strength characteristics of bus body elements. This solution will allow for technical control of buses with bodies of non-bearing structure. In [5], the analysis of the perception of comfort of bus passengers based on the coefficient of passenger traffic and time in the vehicle is carried out. However, the paper does not take into account the factor involving the deterioration of the properties of the bus body during operation. In [6], intelligent transport systems are used. However, the aging of vehicles during operation is not taken into account. Improving the proposed intelligent systems would allow for technical control of public transport bus bodies during operation. In paper [7], the assessment of the dynamic load when generating vibration from the micro profile of the road surface to the car body is considered. However, the cited study is used only at the design stage and does not take into account the further degradation of the elements of the body frame during operation. The proposed approach [7] with further development can be used to predict the technical condition of the body and the deterioration of passive safety during operation. Work [8] pays special attention to the safety of vehicles in the city, while combining a large number of factors. In [8], the forecasting of emergency frequencies is carried out, but their impact on the change in the passive safety of the car during operation is not taken into account. Therefore, such studies can be supplemented with factors influencing the passive safety of passenger transportation in the city. When removing public transport buses that do not meet the requirements of passive safety, it will be important to plan the purchase of buses similar to the proposals of the authors in [9]. Given that public transport buses mainly use air suspensions, optimizing suspension parameters will improve the smoothness of the bus. Such optimization methods are proposed by the authors of [10] by optimizing the operation of air suspension by electronic curation. The authors of [10] prove that such optimization will lead to less vibration loads on the bus body. However, the cited work does not say anything about increasing durability, which could ensure a longer-term compliance of the bus with passive safety requirements [1]. In [11], a review of methods for the study of the road surface was carried out. The quality of the road surface (micro profile) directly affects the durability of the bus body and its compliance with the requirements of passive safety [1]. Therefore, in further studies, it is possible to use the obtained characteristics using the methods from [11] in the study of the degradation of the elements of the body frame during operation. The question of the passive safety of the vehicle can be considered in another way: to prevent it from rollover over using intelligent systems. This approach was proposed by the authors of [12] when driving a truck in the city using a built-in intelligent system. However, passive safety and its constant compliance during the entire life of the bus should be taken into account first of all [13]. The authors of [14] raised the question of the expediency of checking the compliance of the passive safety of public transport buses using numerical methods instead of a full-scale experiment. A comparison of the results of the field experiment and simulation was carried out. The authors of [14] confirmed the right to the existence of methods using simulation to check buses for their compliance with Rules [1]. However, study [14] concerns only new buses and does not take into account the degradation of the material during operation. In [15], back in 2010, the scientific and applied foundations for the formation of passive safety and strength of bus bodies at the design stage were presented. The cited work also did not consider the issue of compliance with the passive safety of the bus during operation.

Thus, having conducted a review of studies reported in [5–15] on the technical control of bus bodies during operation under passive safety conditions, body tests in accordance with the Rules [1] are not carried out. Simulation is also not carried out to check the compliance of the bus with the requirements for passive safety [1] during operation. Therefore, it suggests that it is expedient to conduct a study on the development of technological principles of technical control of bus bodies during operation under passive safety conditions.

3. The aim and objectives of the study

The aim of this study is to develop technological principles of technical control of bus bodies during operation under passive safety conditions. This will make it possible to ensure that the body meets the requirements of passive safety of passenger transportation throughout the service life of the bus.

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

– to substantiate the expediency of improving the technical control system by supplementing visual methods of control by measuring instruments;

– to develop a control technology during restoration repairs;

– to develop a method of controlling the compliance of the bus body with simulation methods, which is based on non-destructive testing, and to conduct simulation modeling of the body's compliance with passive safety conditions.

4. The study materials and methods

The object of our study is the permissible limits of aging of bus bodies during operation and the formation of appropriate recommendations for their control on the conditions of compliance of the body with passive safety rules.

The main hypothesis of the study assumes that using simulation methods, it becomes possible to check the passive safety of bus bodies not only at the design stage by destructive methods but also during operation, by non-destructive methods. The assumptions accepted in the study indicate that during operation the physical and mechanical properties of the body frame material deteriorate. Therefore, over time, there will come a moment of non-compliance of the body with the requirements of the Passive Safety Rules. The simplifications of the procedure for technical control of bodies by non-destructive methods adopted in the current study instead of destructive ones were not used at all in real practice.

For technical control of bus bodies during operation under passive safety conditions, several technology options are proposed, depending on the service life. Subject to the rules of transportation, such technical control is impractical with a service life of up to two years. This restriction is due to the presence of factory corrosion protection, which effectively protects the bus body for two years. After two years of operation, it is necessary to restore anti-corrosion protection of closed cavities of the body frame and restore anti-corrosion protection of the bus bottom.

To implement the first option, the methodology of technical control of the German TÜV is taken as a basis [3]. Unlike TÜV [3], where the control of the bus body is carried out using visual control methods, it is proposed to use an ultrasonic metal thickness gauge. The thickness gauge is required to control the thickness of the walls of the pipes of the spars of the base frame or frame (if any). Such measurements must be carried out with a service life of buses of more than 5 years. If, as a result of measurements, it is found that the thickness of the walls of the pipes of the spars or frame has decreased by 15 %, the bus is not allowed to operate (in accordance with the fourth version of TÜV). However, in Ukraine, the fourth version is not provided according to Resolution No. 137 as of 30.01.2012 [2]. Therefore, buses with damages that make it impossible to continue operation are put on repairs. Thus, it is advisable to introduce amendments to the Resolution's [2] fourth paragraph, which provides for the disposal of the bus body in case of significant corrosive and fatigue damage to the body frame, or frame. However, unlike European practice, in Ukraine carriers will strive to carry out restoration repairs. Therefore, taking into account the peculiarities of the approach to the restoration of buses in Ukraine, it would be expedient to foresee conditions that will allow for restoration repairs. When repairing a bus frame structure during the removal of the body from the frame, quite often the body frame is destroyed. In the case of significant corrosion damage, the bus frame must be replaced. Since the frame is made of alloy steels and heat-treated, any repair work impairs its physical and mechanical characteristics. In the case of non-bearing construction of the bus body, it is allowed to carry out restoration repairs of the bus body only in the factory. As the experience of buses operation and repair practice show, in order to ensure high-quality restoration repair of the body frame, it is necessary to completely replace the frame of the bus body below the windowsill bar. In the factory, body repair repeats the factory technology of manufacturing the bus. This technology of bus body restoration has been introduced at OJSC Ukravtobusprom, Lviv (Ukraine), and is being implemented at Cherkasy Bus JSC in Cherkasy (Ukraine). It is advisable to introduce repair practice in the factory for buses from other manufacturers. It is proposed to revise the TÜV methodology [3] with complete non-admission to operation with the possibility of carrying out restoration repairs in the factory. Such an approach to technical control and the practice of restoration repairs will rationally ensure an adequate level of passive safety of buses during operation.

The second version of technical control is implemented by destructive methods only during the restoration of the bus. To do this, several samples are cut from the elements of the body frame, which do not have obvious corrosion damage and do not need to be replaced. The shape and size of the samples used in the research are shown in Fig. 1.

Then, on a breaking machine, according to a known methodology [16], the pattern of stretching of samples is determined. According to the sample tensile diagrams, the following mechanical characteristics of the body frame elements are determined: yield strength σ_Y, endurance stress σ_E, and relative elongation of δ.

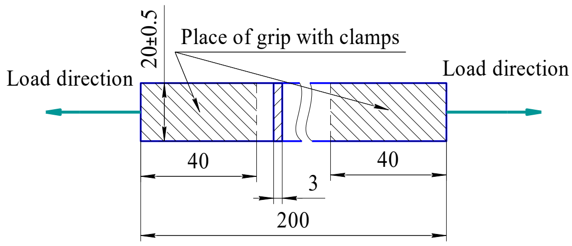


Fig. 1. The shape and size of samples used in the research

The yield strength is determined by the formula:

$$\sigma_Y = \frac{P_Y}{F_0}, \quad (1)$$

where F_0 is the cross-sectional area of the prototype; P_Y – tensile force of the sample at the fluidity of the material. Endurance stress is determined by the formula:

$$\sigma_E = \frac{P_{\max}}{F_0}, \quad (2)$$

where $P_{\max}$ is the maximum tensile force of the sample.

The relative elongation is determined from the tensile diagram along the axis of elongation, which corresponds to the maximum force $P_{\max}$.

The relative elongation of the sample is determined by the formula:

$$\delta = \frac{\Delta l}{L} \cdot 100\,\%, \quad (3)$$

where Δl is the increase in sample length during stretching along the axis of elongation; L – sample length before testing.

The properties of the samples are compared with the properties of the new material from which the corresponding elements of the body frame are made (Steel S235JRG2 PR 15017-2). If the specified mechanical properties do not match, such elements of the body frame are cut out and replaced completely. The third version of technical control is carried out by simulation using the ANSYS R 19.0 (USA) computational software using a finite-element method in accordance with UNECE Rules No. 66 [1]. The simulation procedure using the ANSYS R 19.0 (USA) calculation software by a finite-element method is described in detail in monograph [17]. To systematize the calculations of the strength of the bus body during operation in accordance with UNECE Rules No. 66, a flowchart has been drawn up (Fig. 2).

Similar to methodology from [17], the frame of the bus body is represented by a three-dimensional rod model, which contains the following types of elements: rod, beam (stretching/compression, bending, torsion), truss (stretching/compression), 4-angular plate, 3-angular plate, 8-node octahedron, 6-node triangular prism, 4-node tetrahedron. Each structural element has its local coordinate system. For convenience, all coordinate systems are right-handed. In the local coordinate system, the following attributes of the node are specified: fixing degrees of freedom, elastic fasteners, hinges, moving in the direction of fixed degrees of freedom. The coordinate system of the rod is always oriented in such a way that the X axis is directed along its axis. The cross-section orientation of the rod is rigidly tied to its coordinate system. In addition, the loads on the rod are also set in the local coordinate system of the rod. The coordinate system of the plate is oriented so that the Z axis is directed normal to the plane of the plate, the X axis is parallel to one of the sides of the plate, and the Y axis complements the system of vectors to right sided. In the local system, a normal distributed load on the plate is also set. The coordinate system of a three-dimensional element coincides with the global coordinate system. Degrees of freedom: the node has six degrees of freedom, the rod has 12 degrees of freedom, the plate has 18 or 24. Volumetric elements have 12, 18, or 24 degrees of freedom, three (linear movements) in each node. According to the design documentation for the bus, the following profiles of rods were taken into account: 63×32×2.5, 63×45×3, 80×40×3, 100×54×4.

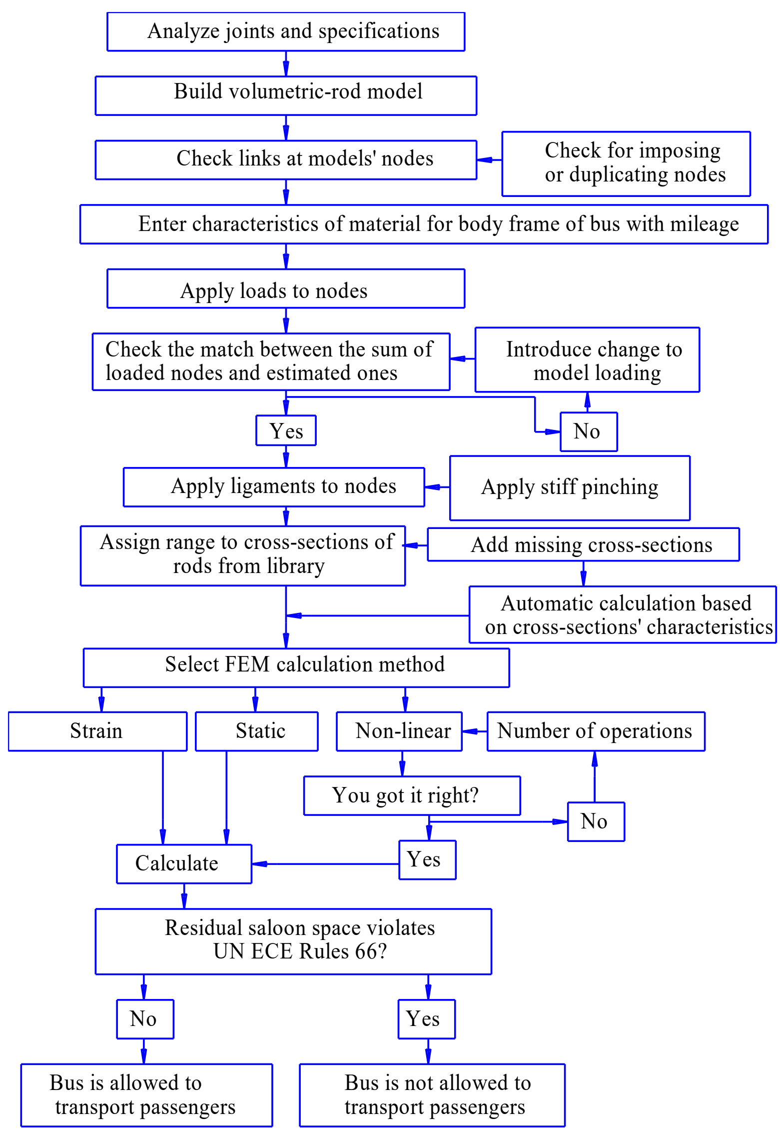


Fig. 2. Flowchart of the algorithm for calculating the strength of the bus body during operation for compliance with the requirements of UN ECE Rules No. 66

In contrast to works [14, 15, 17], the model includes the characteristics of the material of the frame of the bus body, which was already in operation: yield strength σ_Y=37 MPa, endurance stress σ_E=299 MPa, relative elongation δ=16 %. The characteristics of the elements of the body frame with mileage can be determined during restoration repairs of the body under specified operating conditions and at specified service times. The proposed version of technical control involves imitation modeling that must satisfy certain conditions. The first condition is that each section of the tested body is firmly and securely fixed on the test bench with a rigid structure. There should be no local plastic deformation around the attachment points. The second condition is that the place and method of attachment should not prevent the formation of the projected zones of plastic deformation and the work of plastic hinges.

To apply the load to the body section, in accordance with UNECE Regulation No. 66, two requirements were met. The first requirement is that the load is evenly distributed over the upper strapping through a rigid beam. The length of the beam is longer than in the upper strapping to simulate the surface of the earth in the rollover test. The second requirement is that the load is applied to the beam in the center of gravity of the body section. The center of gravity is determined by the masses included in the sections of the power structure and the structural elements connecting them.

The calculation consists of several stages for determining boundary conditions:

1. Based on the terms of technical task for the bus under study, an estimation scheme (Fig. 3) of loads was drawn up to determine the coordinates of the consolidated center of gravity *O* based on the position of the concentrated mass and its value for the following components: driver, engine with attachments, transmission, additional equipment (control system and brakes, fuel tank, spare wheel, batteries, other corresponding components and assemblies), frame body taking into account the exterior, inner plating, and chassis with mounted units.

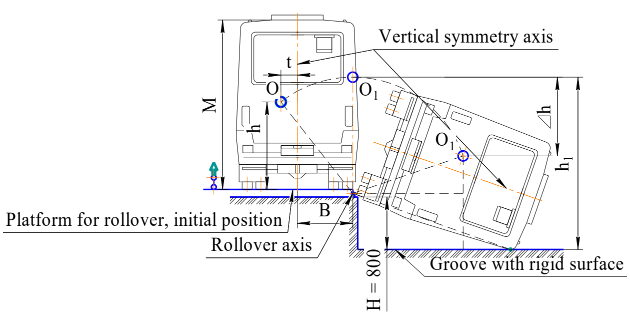


Fig. 3. Estimation scheme of the trajectory of the fall of the bus until the moment of impact in accordance with Rules No. 66 of the United Nations Economic Commission for Europe

We established coordinates of the center of gravity of the bus: height l_k=0.77 m; there is no offset relative to the longitudinal axis of chassis symmetry; the distance from the front axle of the wheels to the theoretical center of gravity in the horizontal direction is shorter by 3 % of the true position calculated from the reactions of the wheels based on real weighing (2349 mm).

2. According to the law of conservation of energy for equally variable rotational motion under the action of gravity, the final angular speed of rotation at the time of impact of the body frame with a shock surface is calculated: ω=2.59 s^{-1}. Since UN ECE Regulation No. 66 requires no additional external influence on the rollover process, except for the effect of gravity, the value of the initial angular velocity in the calculations was taken as zero.

3. With the help of engineering software and working drawings of the bus model BAZ-A079.23, the real value of the radius of rotation of the center of gravity and the corresponding angle of rotation were measured: r=1.22 m; φ=0.28π. Expressing the angular acceleration ε through the angular velocity ω, the time spent on rollover the bus is determined: t=0.68 s.

4. Based on the obtained calculated parameters, the rotating and centripetal acceleration is a_r=4.65 m/s^2, a_{ca}=8.18 m/s^2. Imitation of UN ECE Rules No. 66 by calculation method involves taking into account the resulting acceleration a_{res} when determining the amount of absorption energy of the impact *E*. The obtained values of accelerations and the absorption energy of the impact relate to the material point.

For maximum accuracy of imitation of testing for compliance with UN ECE Rules No. 66, the application of motion restriction links is performed in the nodes of the spatial structure of the body frame, the least malleable to impact deformations: the powerful shape of the bus chassis and the lower thresholds of the left sidewall.

Fig. 4 shows a schematic diagram of installation in accordance with UN ECE Regulation No. 66 when simulating a bus rollover.

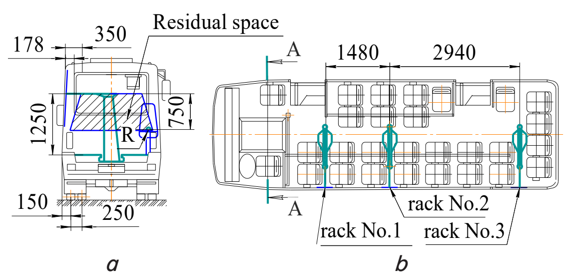


Fig. 4. Schematic diagram of the installation for testing in accordance with Rules No. 66 of the United Nations Economic Commission for Europe: *a* – rear view; *b* – top view

After the bus is tipped to the side, then, in accordance with UN ECE Regulation No. 66, the deformations of the racks should be such that they do not block the safe residual space in the form of a shaded trapezoid shown in Fig. 3. In case of going beyond the tolerance, such a body is rejected and cannot be restored.

5. Results of the study according to the technology of control of compliance with the passive safety of bus bodies during operation

5. 1. Justification of the expediency of improving the system of technical control of bus bodies

In the first version of the technical control, the buses are checked for corrosion damage and cracks. Fig. 5 shows the bus «Bogdan» A092, during the inspection of which corrosive damage to the body cladding was found.

When visually inspecting the outer cladding of the bus body, it was assumed that under the cladding with such corrosive damage, manifestations of structural corrosion are also possible. Therefore, it was decided to partially cut off the outer cladding.

As a result of cutting off the outer cladding, the body frame was opened (Fig. 6).

Fig. 5. Bus «Bogdan» A092 with corrosion damage to the body cladding

Fig. 6. Corrosion damage to the body under the cladding of the city bus «Bogdan» A092

Fig. 6 shows that significant manifestations of structural corrosion were discovered under the cladding, which confirmed the assumption based on a visual inspection of the outer cladding.

If one inspects the bottom of the bus, one can see cracks in the elements of the body frame (Fig. 7).

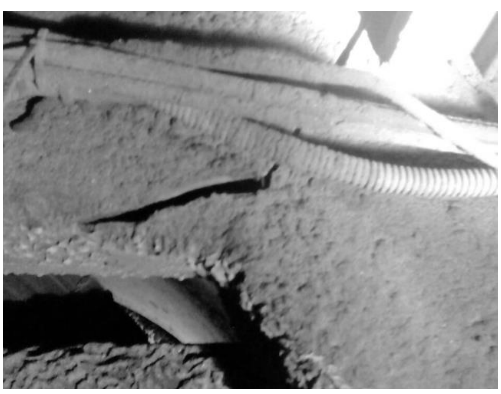


Fig. 7. Fatigue crack in the frame of the base of the city bus «Ataman» A092N6

This type of crack (Fig. 7) is noticeable even on the dirty bottom of the body. However, cracks at the initial stage of formation will be invisible. Therefore, before controlling the bus body, a mandatory preparatory stage should involve washing the body under pressure with subsequent drying.

During operation, damage to the body frame may occur due to the accumulation of condensate in closed cavities. At positive temperatures, the accumulation of moisture in closed cavities does not manifest itself in any way. However, at negative temperatures, this can lead to the destruction of the frame pipes. Fig. 8 shows a rack that was damaged by the freezing of water in it in winter.

Fig. 8. Crack in the vertical rack of the cabin as a result of freezing of the accumulated moisture of the city bus «Ataman» A092H6

Such a rack (Fig. 8) is completely replaced since the compliance of the bus with the UN ECE rules No. 66 will directly depend on its strength. Drainage holes are also drilled to flow out the condensate from the rack.

There are buses with decorative plastic rack pads. Therefore, when controlling the body, the decorative claddings of the racks must be dismantled.

During the operation of the bus, cracks may also form as a result of design calculations without taking into account a safety factor of more than 1.0. As a result, fatigue cracks can form prematurely. For example, Fig. 9 shows a fatigue crack in the autonomous heater compartment.

Fig. 9. Fatigue crack in the bottom of the compartment of the autonomous heater of the city bus «Ataman» A092N6

During the control of this type of damage (Fig. 9), a prerequisite is the opening of all the hatches of the bus, which will make it possible to track cracks in the light.

The formation of such cracks does not have a significant impact on the passive safety of the bus body. In this case, a complaint is filed with the bus manufacturer. In the department of the chief designer, a technical solution is being developed to eliminate this deficiency. Usually, a new technical solution involves welding cracks and welding additional reinforcing elements.

Fig. 5 to 9 show that visual control methods make it possible to fix only visible damage and do not carry any information about the condition of the closed cavities of the body frame. Cutting out a fragment of the body frame, you can see the real thickness of the pipe profile (Fig. 10).

Fig. 10. Pipe fragment (140×60×3 mm) of the base of the body frame is affected by corrosion

Fig. 10 demonstrates that full control will be carried out when cutting out individual fragments of the body frame pipes. However, this method is irrational and requires an alternative method of control. A rational method would be the use of ultrasonic metal thickness gauge. Fig. 11 shows the ultrasonic metal thickness gauge Walcom TM-881 (China).

Fig. 11. Ultrasonic metal thickness gauge Walcom TM-881

The ultrasonic metal thickness gauge allows the metal thickness to be measured in a non-destructive way. Walcom TM-8816 is an ultrasonic metal thickness gauge with a built-in sensor and the ability to set the appropriate sound speed depending on the material being measured. It is designed to measure the thickness of metal products and the thickness of materials, for example: steel, cast iron, aluminum, red copper, brass, zinc, quartz glass, polyethylene, gray cast iron. The measurement range is from 1.0–200 mm, which makes it possible to estimate the thickness of the body frame pipes (from 2 to 4 mm depending on the pipe profile). The speed of sound varies between 500–9990 m/s. Accuracy of the device is ±0.5 % of the measured value. The operating temperature range is in the range of 0–40 °C, at a relative humidity of <85 %.

Thus, the proposed control method, using ultrasonic metal thickness gauge, will allow for rational control of buses with correct measurement of the thickness of the walls of the pipes of the body frame.

5. 2. Results of testing the elements of the bus body frame according to the control technology during restoration repairs

The second option of technical control can be implemented during the repair of the bus. To carry out such control, prototypes are cut in accordance with (Fig. 1) in an amount of at least five. Samples are cut from the frame of the base, sidewall racks (Fig. 4), or other elements of the body frame. Cutting samples from the frame is not allowed. Then the mechanical properties of the cut samples are determined.

According to the developed control technology to determine the mechanical properties of the elements of the body frame, six samples were tested on the breaking machine P-5 according to ISO 6892-1:2019 (Fig. 12).

Fig. 12. Testing samples of body frame elements on the breaking machine R-5 according to ISO 6892-1:2019

Fig. 12 depicts the test of one of the fragments of the body frame of the eight-year-old Bogdan A092 bus with a mileage of 850 thousand km. For testing, 6 samples of body frame elements were cut that do not have obvious corrosion damage. Such elements of the body frame, as repair practice shows, are not cut out during the restoration of the body.

As a result of the tests, tensile diagrams were built and, according to the obtained diagrams, the mechanical properties of the samples were calculated from formulas (1) to (3) (Table 1).

Table 1 gives, for comparison, the steel grade from which the body frame is made (Steel S235JRG2 PR 15017-2) and its main characteristics.

During each restoration, such tests of body frame fragments will provide statistical data on the loss of strength of the body frame elements depending on the service life and mileage.

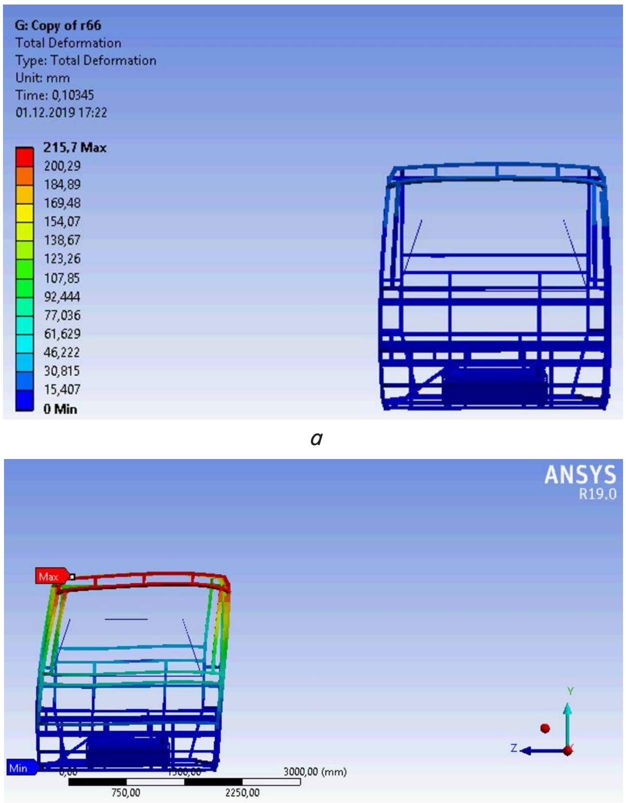
Table 1

Comparison of the pipe frame material of the new and eight-year-old bus

Parameter	Properties of the new material Steel S235JRG2 PR 15017-2	Properties of sample material of an eight-year-old bus					
		1	2	3	4	5	6
σ_Y, MPa	235	–	–	–	–	37	143
σ_E, MPa	340	191	102	175	249	299	294
δ, %	23	2	1	5	13	16	6

5. 3. Results of simulation modeling of the compliance of the bus body with the conditions of passive safety

The third version of technical control is implemented according to the results of testing the materials of the frame of the bus body that was in operation. For simulation, the properties of the material that have the highest value of the endurance limit (sample No. 5) were selected: σ_Y=37 MPa, σ_E=299 MPa, δ=16 %. Fig. 13 shows the bus during simulation in accordance with UN ECE Regulation No. 66.



a

b

Fig. 13. A bus during simulation in accordance with United Nations Economic Commission Rules No. 66: *a* – before rollover; *b* – after rollover

Table 2 gives the comparative test results of the new bus [17] and the bus with a service life of 8 years.

Table 2

Comparison of the deformation of racks of the new and eight-year-old bus

Deformation of the bus racks Δe, mm	Rack number		
	1	2	3
New [17]	178	135	74
Eight-year-old	393	344	282

The results of simulation show that the bus after eight years of operation will no longer meet the requirements of UN ECE Rules No. 66.

6. Discussion of results on the development of technological principles of technical control of bus bodies

In contrast to existing methods of controlling bus bodies [1–3], as a result of the research, the technological principles of technical control of bus bodies during operation have been formed, which provides for the possibility of checking them for compliance with UN ECE Rules No. [1].

According to the results of the first visual inspection option, mechanical damage to the bus body can be detected: chips and scratches of the paintwork, damage to the corrosion protection of the bottom and wheel arches. Such damage does not affect the passive safety of the bus body. Timely detection of such damage will avoid further development of bus corrosion. If surface damage to the bus body is not detected in a timely manner, this can lead to deeper destruction of the body (Fig. 4). At the same time, sites of corrosive damage of a larger area are formed, which will be open to the aggressive effects of salt and sand agents against icing of roads. As a result, sites of fatigue destruction will be intensively formed under the action of cyclic loads. Such damage will also be detected by visual inspection. On such a bus (Fig. 4), the cladding panels are made of steel without zinc coating. For admission to operation, it is necessary to eliminate corrosive damage to the cladding of the body frame. Fig. 5 demonstrates that the body cladding has through destruction in some places. Therefore, in this case, a decision is made to replace the body cladding with a new one. To avoid corrosion damage in the future, it would be advisable to use a cladding with double-sided galvanizing.

Significant structural destruction (Fig. 6) is explained by the fact that the technology of manufacturing the body is imperfect. The bus body is welded completely, and, after that, anti-corrosion protection is carried out. As a result, uncovered places remain between the body frame and the cladding. Such a bus will be allowed to operate subject to full restoration of the body. As the repair practice shows, basically all buses that have corrosive damage to the cladding (Fig. 5) also have manifestations of structural corrosion of the body frame. Thus, the presence of corrosion of the body cladding will be the basis for the prohibition of the operation of the bus. Structural corrosion leads to a violation of the geometry of the body. Therefore, high-quality repairs can be carried out in the factory using special technological equipment. Repair organizations can also ensure proper repairs. In addition, this technology needs to be improved as follows. The pipes of the body frame under the cladding should be covered with anti-corrosion, and in the places of welding the cladding with conductive high-temperature primer.

This type of crack (Fig. 7) occurs as a result of systematic overload by passengers. With such damage, repair will be effective when replacing a damaged fragment of the body frame. When welding the resulting crack during operation, repeated destruction will occur. Very rarely, similar destruction can occur due to non-compliance with the manufacturing technology in the factory (poor-quality weld). This leads to overstrains of individual elements of the body frame (impaired equivalence of the body) and the rapid formation of fatigue cracks. Therefore, it is also necessary to carry out a visual inspection of the bus body and its bottom in the initial period of operation – the first 100 thousand km (warranty period).

Since the frame of the bus body is made of closed-section pipes, with such controls [2] internal closed cavities are ignored. Unlike [2], where only visual inspection is carried out, the use of measuring instruments makes it possible to determine the thickness of the pipe walls. This is made possible by the use of ultrasonic metal thickness gauge.

There are accumulations of sites of fatigue destruction that cannot be visually detected even when measuring their thickness. Such sites of fatigue destruction remain unattended during repairs. Therefore, during the restoration repair of the body, the second version of technical control with determining the mechanical properties of the elements of the body frame will be an obligatory method of control. As can be seen from Table 1, in samples 1–4, the yield strength is not tracked at all. In sample No. 5, the value of the yield strength σ_Y is 6.35 times less, and, in sample No. 6, less than 1.64 times. Endurance stresses σ_E in all samples are impaired by 1.14–3.33 times. The relative elongation δ will worsen by 1.43–23 times, which confirms the loss of plasticity of such material. The decrease or absence of fluidity is also explained by the loss of plasticity of the material of the bus frame pipes. UN ECE Rules No. 66 [1] regulate the maximum deformations of the bus body. When such an eight-year-old bus rolls over, not only increased deformations of the body frame are possible but the destruction of its racks, which is generally unacceptable. Therefore, at the stage of restoration repair, when detecting fragments of pipes with impaired physical and mechanical properties, these pipes are cut out completely. The next samples are then cut and a further series of materials testing is carried out. In case of non-compliance of the frame material of all pipes with the characteristics of the new material, such a body must be completely replaced. However, there are cases when there is no visual damage to the bus body and there is no need for restoration yet. In this case, it would be advisable to conduct the third option of technical control. To obtain the initial data for simulation, you can use the results of the second version of technical control.

According to the results of the third version of technical control (Table 2), it can be seen that when the endurance limit deteriorates by 1.14 times and the yield strength by 6.35 times, the deformation of the racks of the eight-year-old bus increases by 2.21–3.81 times. Therefore, such a bus no longer complies with UN ECE Rules No. 66. In the case of controversial situations, in order to check the compliance of the bus with UN ECE Rules No. 66, there will be a need for additional cutting of the sample from one of the bus racks. Such a decision can be made only as a last resort. Thus, full technical control of bus bodies during operation under passive safety conditions is possible taking into account all three proposed options.

Thus, our studies, in contrast to [5], take into account the passive safety of passenger transportation, which, with long service life, will affect the comfort of passenger transportation. Since the weakening of the structure of the elements of the body frame will lead to an increase in tremors from the roadway to the passenger seats.

Intelligent transport systems [6] could be supplemented in further studies by strain gauge of bus bodies. This would also allow controlling the deformation of the elements of the body frame, an increase in which may indicate a deterioration in the mechanical properties of the material.

Determining the dynamic load when generating vibration from the micro profile of the road surface to the car body, which is used at the design stage [7], is advisable to use during operation. This, in further studies, in combination with methods [11], would make it possible to predict the deterioration of the mechanical properties of the material and the onset of the moment of non-compliance with the requirements of Rules [1].

Planning of bus purchases [9] will become more correct when the main factor in replacing the bus is its non-compliance with the requirements of UN ECE Rules No. 66 during operation and the inexpediency of carrying out restoration repairs.

Unlike [14, 15, 17], where simulation of the rollover of only a new bus is carried out in accordance with UN ECE Rules No. 66, the developed technological principles allow such tests to be carried out taking into account the degradation of the metal during operation. This becomes possible thanks to research on the breaking machine of samples that are cut out of the body frame during restoration repairs. The obtained values of the physical and mechanical properties of the degraded metal of the body frame are entered into the simulation model, which makes it possible to control the compliance of the bus with the conditions of passive safety during its operation.

When introducing buses into real operation, it is also necessary to take into account the limitations of the presented technological principles of technical control. Control according to the developed technological principles applies only to buses that are intended for the transport of passengers, the passive safety of which is regulated in accordance with UN ECE Rules No. 66. In the absence of information on the degradation of the body frame elements, control is limited to visual control and ultrasonic means of measuring thickness of metal.

The disadvantages of the study include an increase in the time norms for technical control in comparison with classical visual control. As well as additional costs for the purchase of measuring instruments and for laboratory tests of prototypes.

The development of this study may consist in further experimental research to determine the physical and mechanical properties of the elements of the body frame at different terms and conditions of operation of buses. The accumulated statistics will increase the efficiency of simulation when checking the passive safety of the bus in accordance with UN ECE Rules No. 66, taking into account different operating conditions.

Thus, the proposed technological principles of technical control of bus bodies under passive safety conditions make it possible to control the technical condition of buses throughout the entire service life in accordance with Rules [1], which was previously impossible.

7. Conclusions

1. The expediency of improving the technical control system of bus bodies in addition to the visual methods of monitoring measuring instruments by introducing an ultrasonic thickness gauge of metal that has not previously been used to control car bodies is substantiated. This thickness gauge makes it possible to determine the thickness of pipes of a closed type of body frame, which decreases under the action of corrosion during operation.

2. A control technology has been developed, which is implemented during the restoration repairs of the bus, which involves cutting metal samples to check their physical and mechanical properties. When implementing this technology, it was experimentally proved that during the restoration repair of the Bogdan A092 bus with a mileage of 850 thousand km in four of the six samples, the yield strength was not tracked at all, the endurance limit decreased by 1.14–3.33 times. Experimental studies confirm the effectiveness of the developed control method.

3. A method of controlling the compliance of the bus body with simulation methods during operation under passive safety conditions in accordance with the requirements of UN ECE Rules No. 66 has been developed, which made it possible to abandon destructive control methods. The non-destructive method of control makes it possible to check the bus body from passive safety conditions in accordance with the requirements of UN ECE Rules No. 66 in operational conditions, which was not previously possible. Based on the developed

methodology, the bus body was checked for compliance with passive safety conditions in accordance with the requirements of UN ECE Rules No. 66 by simulation methods. As a result of the experiment, it was found that the deformation of the racks of an eight-year-old bus increases by 2.21–3.81 times, which indicates the inadmissibility of operating the bus.

Conflicts of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The study was conducted without financial support.

Data availability

Manuscript has no related data.

References

1. 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: https://op.europa.eu/en/publication-detail/-/publication/6d1479db-1195-41eb-837b-8e0de970dcaf/language-en/format-PDF/source-search
2. Postanova No. 137 vid 30.01.2012 r. Pro zatverdzhennia Poriadku provedennia oboviazkovoho tekhnichnoho kontroliu ta obsiahiv perevirky tekhnichnoho stanu transportnykh zasobiv, tekhnichnoho opysu ta zrazka protokolu perevirky tekhnichnoho stanu transportnoho zasobu (2012). KM No. 485 vid 23.09.2014, No. 1138 vid 23.12.2015, No. 141 vid 10.03.2017. Kabinet Ministriv Ukrainy. Kyiv: Parlamentske vydavnytstvo, 37. Available at: https://zakon.rada.gov.ua/laws/show/137-2012-%D0%BF#Text
3. Verband der TÜV e. V. TÜV Bus-Report, 2018. Available at: https://mitglieder.tuev-verband.de/dok_view?oid=721019
4. Ruban, D. P., Krainyk, L. V., Ruban, H. Ya. (2021). Otsinka pasyvnoi bezpeky kuzova avtobusa pid chas ekspluatatsiyi. Materials of IX-th international scientific and technical internet-conference «Problems and prospects of development automobile transport». Vinnytsia, 229–231. Available at: https://atmconf.vntu.edu.ua/materialy2021.pdf
5. Shen, X., Feng, S., Li, Z., Hu, B. (2016). Analysis of bus passenger comfort perception based on passenger load factor and in-vehicle time. SpringerPlus, 5 (1). doi: https://doi.org/10.1186/s40064-016-1694-7
6. Iliopoulou, C., Kepaptsoglou, K. (2019). Combining ITS and optimization in public transportation planning: state of the art and future research paths. European Transport Research Review, 11 (1). doi: https://doi.org/10.1186/s12544-019-0365-5
7. Agostinacchio, M., Ciampa, D., Olita, S. (2013). The vibrations induced by surface irregularities in road pavements – a Matlab® approach. European Transport Research Review, 6 (3), 267–275. doi: https://doi.org/10.1007/s12544-013-0127-8
8. Intini, P., Berloco, N., Cavalluzzi, G., Lord, D., Ranieri, V., Colonna, P. (2021). The variability of urban safety performance functions for different road elements: an Italian case study. European Transport Research Review, 13 (1). doi: https://doi.org/10.1186/s12544-021-00490-6
9. Hansson, L. (2011). The tactics behind public transport procurements: an integrated actor approach. European Transport Research Review, 3 (4), 197–209. doi: https://doi.org/10.1007/s12544-011-0057-2
10. Sun, X.-Q., Cai, Y.-F., Yuan, C.-C., Wang, S.-H., Chen, L. (2018). Fuzzy Sliding Mode Control for the Vehicle Height and Leveling Adjustment System of an Electronic Air Suspension. Chinese Journal of Mechanical Engineering, 31 (1). doi: https://doi.org/10.1186/s10033-018-0223-8
11. Nguyen, T., Lechner, B., Wong, Y. D. (2019). Response-based methods to measure road surface irregularity: a state-of-the-art review. European Transport Research Review, 11 (1). doi: https://doi.org/10.1186/s12544-019-0380-6
12. Jin, Z., Li, J., Wang, H., Li, J., Huang, C. (2021). Rollover Prevention and Motion Planning for an Intelligent Heavy Truck. Chinese Journal of Mechanical Engineering, 34 (1). doi: https://doi.org/10.1186/s10033-021-00605-z
13. Nemeth, J. (1990). The Role of Active and Passive Safety in Bus Engineering. SAE Technical Paper Series. doi: https://doi.org/10.4271/902273
14. 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
15. Holenko, K. E., Horbai, O. Z., Krainyk, L. V. (2010). Otsinka totozhnosti modeliuvannia vidpovidnosti avtobusiv pravylu No. 66 YeEK OON ta eksperymentalnykh vyprobuvan. Visnyk Natsionalnoho tekhnichnoho universytetu «KhPI»: zbirnyk naukovykh prats. Tematychnyi vypusk: Avtomobile- ta traktorobuduvannia, 1, 101–109. Available at: http://repository.kpi.kharkov.ua/handle/KhPI-Press/18327
16. ISO 6892-1:2019. Metallic materials – Tensile testing – Part 1: Method of test at room temperature. Available at: https://www.iso.org/standard/78322.html
17. Horbai, O. Z., Holenko, K. E., Krainyk, L. V. (2013). Mitsnist ta pasyvna bezpeka avtobusnykh kuzoviv. Lviv: Vydavnytstvo Lvivskoi politekhniky, 276. Available at: https://vlp.com.ua/node/10385