Simulation of the TATA 079 suburban bus rollover tests in accordance with UN/ECE Regulation No. 66

Kostyantyn Holenko[1], *Aleksandr* Dykha[1], *Tomasz* Kalaczyński[2] , *Serhii* Matiukh[1] and *Orest* Horbai [3]

[1]Khmelnitskyi National University, 29016, Instytutska 11, Khmelnitskyi, Ukraine
[2] Politechnika Bydgoska im. Jana i Jędrzeja Śniadeckich, Al. prof. S. Kaliskiego 7, 85-796 Bydgoszcz, Poland
[3]Lviv Polytechnic National University, 79000, 12 Stepan Bandera Str., Lviv, Ukraine

Abstract. This work is a logical continuation of studies presented in the author's previous publications [1,2,3] on establishing the analytical application features of the developed methodology for simulating natural tests in accordance with UN/ECE Regulation No. 66. [4], as well as evaluating the identity between calculated and experimental results of checking the reserve of cabin space. The relevance of the proposed methodology is primarily related to the need to comply with the requirements of the current Regulation regarding the level of passive safety of passengers in the cabin during the certification of buses: a real-life approach to testing is conducted with a series of crash tests, which lead to the inevitable destruction of the bus body frame. We would like to remind that the specific weight of the body cost in the total cost of the bus, depending on its type, can reach up to 50% of its price, which leads to exorbitant costs during the certification of road prototypes before the start of their commercial operation.

1 Introduction

It will be recalled that the regulatory requirements of UN/ECE Regulation No. 66. are imposed on all models of single-deck vehicles adapted for the transportation of 16 or more passengers [4], and need to carry out a check on the preservation of the remaining living space during a side rollover crash test by one of the legally permissible methods: natural tests or imitation calculated. It is obvious that the calculation method, which involves the analysis of the strength and deformation of the bus body frame upper part, has the greatest efficiency from an economic point of view. At the same time, the use of simplification and approximation algorithms in the transition from a structurally complete body frame to a spatial construction of roof sections leads to a significant discrepancy between the obtained research results in relation to the full-scale experiment of a fully equipped bus. Taking into account the admissibility of choosing an appropriate method of passive safety analysis within the framework of UN/ECE Regulation No. 66 by the relevant certification centre or the

manufacturing plant itself, recently there has been a trend of developing and implementing own methods of researching the strength and residual space of passenger vehicle cabins.

2 Literature review

The methodology proposed in the presented work for testing bus bodies for compliance with UN/ECE Regulation No. 66. in an analytical way originates in the author's works [1,2,3], where studies of the BAZ (TATA) city bus rod model behaviour in the APM WinMachine software environment under the influence of loads were outlined. These works also revealed the factors affecting the final amount of energy to be absorbed by the body during rollover: the suspension roll effect; the distribution of masses of nodes and aggregates by sections of the body, which distorts it and allows non-simultaneous contact of the above-mentioned edge with the impact surface, etc. Part of such losses for energy conversion is also set out in UN/ECE Regulation No. 66 in the section dealing with energy ($E_T = 0.75\, Mg\Delta h$) [4]. Speaking about the optimization of the city bus bodies structure strength, for example, of the Low-entry type, it is advisable to refer to the publication [5]. The process of simulating tests of any impact by the finite element method can be presented in an Explicit and Implicit form when solving the equations of motion. The difference between these approaches is disclosed in publications [6-8]. In turn, these approaches to the solution are basic in solving the problems of the rollover cases, which are considered the most dangerous of all types of road accidents in terms of the number of fatalities, and therefore are so relevant for research in the scientific field. Mátyás Matolcsy, who has collected and analysed more than 300 facts of road accidents with side rollovers during the last decades, is a well-known scientist in this topic [9]. The review of literary sources can be completed with a dissertation [10], which thoroughly discloses the issue of boundary conditions formation and calculations in the RADIOSS SMP environment of a medium-class intercity bus.

3 Boundary conditions and calculation

The BAZ-A079.23 (TATA 079) suburban bus model (Fig. 1a) with a curb weight of 5540 kg and axle weight distribution of 2670 kg – front axle and 2870 kg – rear one, respectively (total weight is 7512 kg) was chosen as the object of establishing the identity between the developed methodology for compliance with UN/ECE Regulation No. 66 and natural tests. The normative definition of mass in the equipped state means the mass of the vehicle without passengers and cargo, but taking into account the 75-kilogram mass of the driver, the mass of fuel (90% of the fuel tank capacity specified by the manufacturer), coolant, lubricant, tools and a spare wheel, if this is provided. Let's determine the center of mass of the studied model (Fig. 1b,c):

l_1 - distance from the tipping point A to the reduced center of mass (CM) of the driver, mm;
l_2 - distance from point A to the center of the motor with attached equipment, mm;
l_3 - distance from point A to the center of the transmission with retarder and attached equipment, mm;
l_4 - distance from point A to CM of additional equipment (control and brake system, fuel tank, spare wheel, batteries, other relevant units and units), mm;
l_5 - distance from point A to the CM of the bus body frame, taking into account external and internal cladding, windows and doors, mm;
l_6 - distance from point A to the CM of seated and standing passengers, the rest of the useful area of the bus cabin, mm. This parameter is excluded from the bus load scheme according to the conditions of UN/ECE Regulation No. 66, but is used to check the mass balance calculation;

l_7 - distance from point A to CM of the chassis with attached equipment, mm;
l - the distance from point A to the edge of the roof B;
m_1 ... m_7 – corresponding masses of nodes, aggregates and equipment.

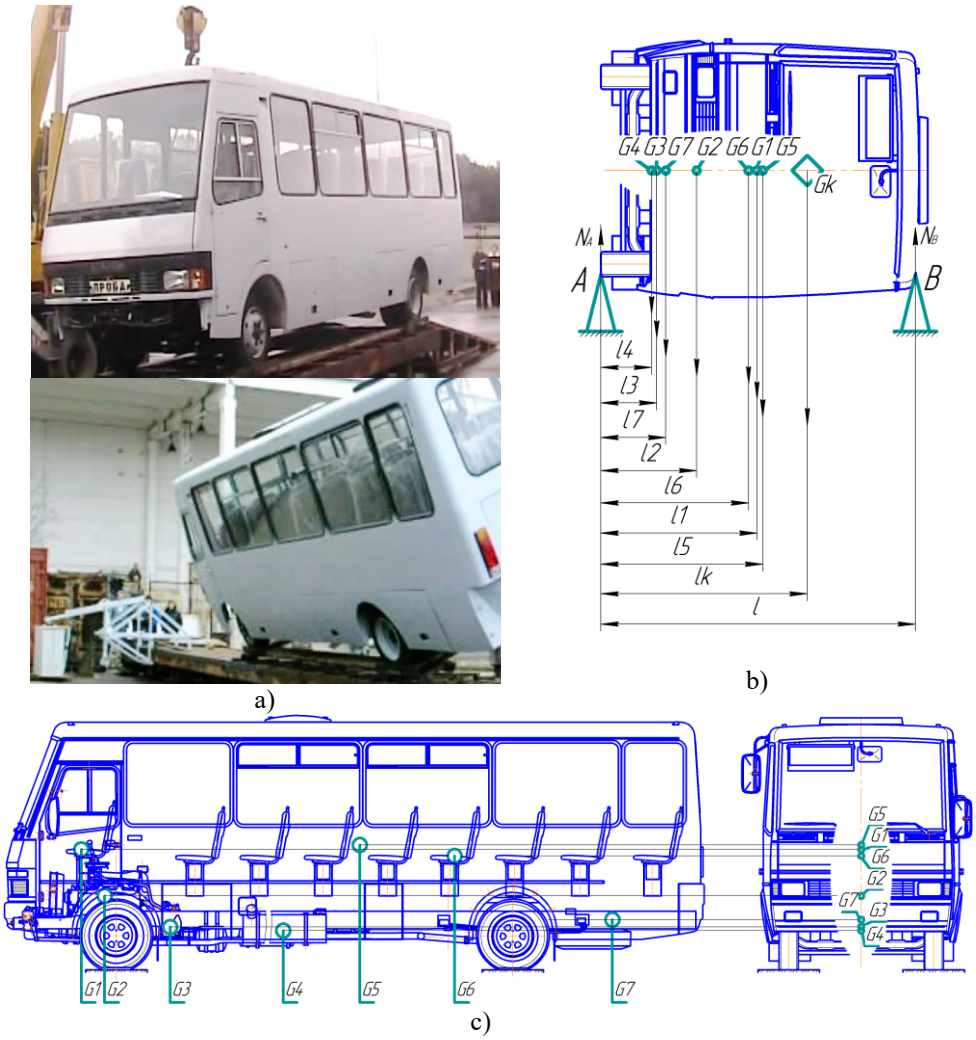


Fig. 1. The object of research in accordance with UN/ECE Rugulation No. 66: a) full-scale model; b,c) determination of the composite centre of mass.

Table 1. Distances and masses characteristics of the TATA 079 model.

Distance from point A to the centres of mass of the corresponding nodes	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l
mm	1375	844	492	447	940	1301	572	2800
Equipped mass of the relevant nodes and aggregates of the bus	m_1	m_2	m_3	m_4	m_5	m_6	m_7	M_k
kg	75	450	300	765	2840	1972	1110	5540

Let's determine the reactions of the bus supports in the transverse plane (Fig. 1b) - write down the equation of static equilibrium:

$$\begin{cases}\sum F_y = 0 \\ \sum M_A = 0\end{cases}; \quad \begin{cases}N_A + N_B - G_1 - G_2 - G_3 - G_4 - G_5 - G_7 = 0 \\ N_B l - G_1 l_1 - G_2 l_2 - G_3 l_3 - G_4 l_4 - G_5 l_5 - G_7 l_7 = 0\end{cases} \tag{1}$$

Determination of reaction N_B:

$$N_B = g(m_1 l_1 + m_2 l_2 + m_3 l_3 + m_4 l_4 + m_5 l_5 + m_7 l_7)/l = 9262.11\ N \tag{2}$$

Determination of reaction N_A:

$$N_A = g(m_1 + m_2 + m_3 + m_4 + m_5 + m_7) - N_B = 45085.29\ N \tag{3}$$

Checking: sum of the reactions N_A and N_B must be equal to the weight of the bus:

$$M_k = (N_A + N_B)/g; \qquad M_k = (45085{,}29 + 9262{,}11)/9.81 = 5540\ kg \tag{4}$$

Let's determine the position of the bus CM in the transverse plane (Fig. 1b):

$$\sum M_A = 0\text{: } N_B l - G_k l_k = 0; \quad l_k = N_B l / M_k \cdot g;$$

$$l_k = N_B l / M_k \cdot g = 9262{,}11 \cdot 4{,}53/5540 \cdot 9{,}81 = 0{,}77\ m \tag{5}$$

Let's write down the law of energy conservation for rotational motion under the action of gravity according to the scheme of tests for compliance with UN/ECE Rugulation No. 66 (Fig. 2):

$$T_1 - T_0 = \sum A(G) = Gh = M_k \cdot g \cdot h, \tag{6}$$

Where: h is the change in the height of the CM from p. Cg^1 to Cg^2 on fig.2.

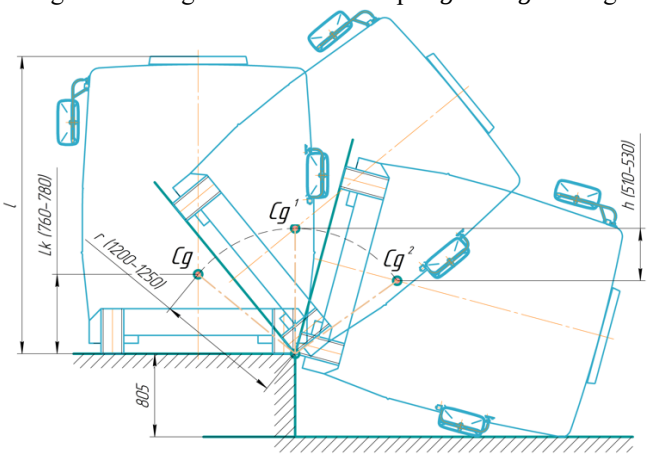


Fig. 2. Calculation diagram of the bus rollover with the centre of mass Cg in accordance with UN/ECE Regulation No. 66.

Unlike mentioned publications [1-3] we will apply another approach within this scientific work - so-called "drop test" module, which is part of the Ansys Explicit Dynamics, but first we will have to understand the theory of calculations using the finite element method (FEM). So, in the general case, any static FEM analysis is determined by a simple linear equation (7), in which the concept of time is absent (static process):

$$[k]\{x\} = \{F\} \tag{7}$$

On the other hand, dynamic analysis (also called transient or modal analysis) follows a more complex governing equation of the form:

$$[m]\{\ddot{x}\} + [c]\{\dot{x}\} + [k]\{x\} = \{F\}, \tag{8}$$

where:
$[m], [c], [k]$ - mass matrix, damping matrix and stiffness matrix, respectively;
$\{\ddot{x}\}$, $\{\dot{x}\}$, $\{x\}$ – acceleration, velocity and displacement, respectively;
$\{F\}$ – load vector

An Implicit solution is a solution in which the current values at one time step are based on the values calculated at the previous time step - this is also called the Euler time integration scheme. In the explicit analysis, instead of $\{x\}$, we solve $\{\ddot{x}\}$, and bypass the inversion of the complex stiffness matrix in this way - we just need to invert the mass matrix $[m]$.

Unlike the Implicit scheme, which is unconditionally stable for large time steps, the Explicit scheme is conditionally more stable. The Explicit calculation is stable when the time step size is smaller than the critical time step size of the investigated structure, otherwise the solution may be misleading by results. Explicit integration schemes use the central difference method to calculate the accelerations and velocities at the current time step (tn), and then determine the unknown displacements at the next time steps (tn+1):

$$\dot{x} = \frac{x^{t+\Delta t} - x^{t-\Delta t}}{2\Delta t};\ \ddot{x} = \frac{x^{t+\Delta t} - 2x^{t} + x^{t-\Delta t}}{2\Delta t^2}, \tag{9}$$

The time step for explicit calculations (Explicit) is calculated based on the characteristic length of the element (L_e) and the speed of wave propagation (c) in the medium or material in which the stress wave propagates. The characteristic length of an element is the shortest distance in the finite element through which a stress wave can pass, so the time step scale factor (TSSF) is selected 0.9 and was used to ensure necessary quality criteria are considered:

$$\mathrm{c} = \sqrt{\frac{E(1-\upsilon)}{\rho(1+\upsilon)(1-2\upsilon)}}, \tag{10}$$

where: υ is Poisson's ratio; ρ is the density of the material.

The characteristic length L_e is calculated on the basis of the element geometric properties and, for example, for an octahedron, it is written as follows:

$$L_e = \frac{V}{A_{max}}, \tag{11}$$

where: V is the volume of the final element; A_{max} is the largest area of the final element.

Returning to the actual calculation parameters in Ansys Explicit Dynamics, it should be noted that the corresponding time increment (step) is equal to 1.139E-07 s, which, for example, for a time interval of 0.01 s is at least 87796 iterations - so many intermediate states of the model will be calculated in the process analysis of the bus frame stress-strain state. Our calculations easily turn into months of continuous PC computing considering that 2.4 s passes from the moment the bus centre of mass passes from the uppermost position in p. Cg^1 to p. Cg^2, which corresponds to the moment of contact with the impact surface (Fig. 2). The time of the CM fall (2.4 s) can be determined by calculation, but we will use the Ansys Rigid Dynamics module to analyse the kinematics of absolutely rigid bodies (Fig. 3) - we will simulate the mass Cg rotation according to the boundary conditions of the scheme in Fig. 2 relative to the position and dimensions of the real bus. Let's measure the time for the CM travel equal to 0.51 m along the vertical axis Y (Fig. 3) - the time value is 2.4 s (Fig. 3).

Let's apply the "drop test" functionality in the Ansys Explicit Dynamics module - place our calculated FEA-model of the TATA 079 bus frame in a position that exactly corresponds to the moment preceding the body contact with the impact surface (Fig. 4).

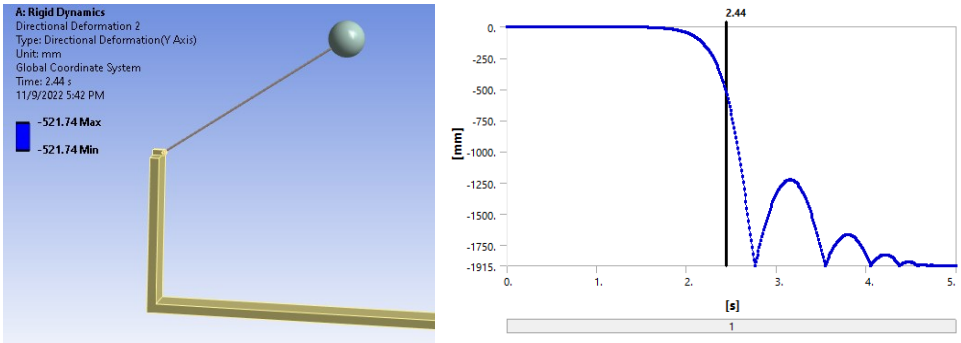


Fig.3. Rigid Dynamics Determining the time of fall from point Cg^1 to p. Cg^2 in the Ansys Rigid Dynamics environment.

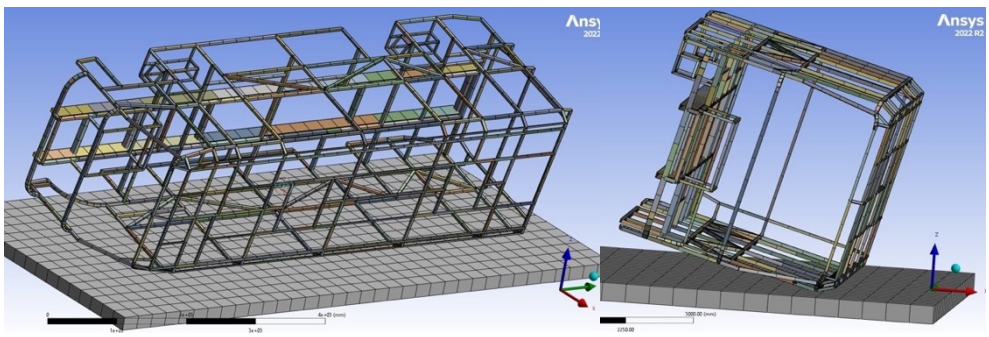


Fig. 4. FEA-model of the TATA 079 bus body frame under the conditions of tests for compliance with UN/ECE Regulation No. 66.

Our calculation model is a spatial structure of the body frame in accordance with the manufacturer's drawings and has a mass of M_m= 980 kg (material is Steel 20), although the actual mass of the bus model should be M_k=5540 kg, as defined above in (4). Therefore, we need to compensate for the lack of mass, equal to 5540 – 980 = 4560 kg, in order to preserve the real value of the impact energy. Given that the impact energy corresponds to the potential energy of rotational motion under the action of gravity (6) with a change in the position of the CM from point Cg^1 to p. Cg^2 (h= 0.51 m in Fig. 2), we will calculate the new drop height h_2 of our body frame model, at which the value of the potential energy will be preserved:

$$M_k gh = M_m gh_2; \quad h_2 = \frac{M_k gh}{M_m g} = \frac{5540 \cdot 0{,}51}{980} = 2{,}88\, m \tag{12}$$

In addition to the height of the bus drop set in (12), we are going to add fixed support to the concrete slab (impact surface) and its absolute rigidity to prevent energy dissipation and obtain the maximum possible deformation of the bus body. Calculation of the fall process with a duration of 0.114 s in Ansys Explicit Dynamics took 49 hours on a workstation with the following characteristics: 2 Intel Xeon physical processors (24 cores in total), RAM 48 Gb, NVIDIA GeForce 4Gb video. In the absence of optimization measures (recalculation of the fall height to compensate for the mass; setting the model in the lowest position preceding the impact), the total calculation time would increase at least tenfold, taking into account the duration of the overturning process of 2.4 s, defined in Fig. 3.

According to the calculation results, the following maps of model deformations at intermediate time moments were obtained:

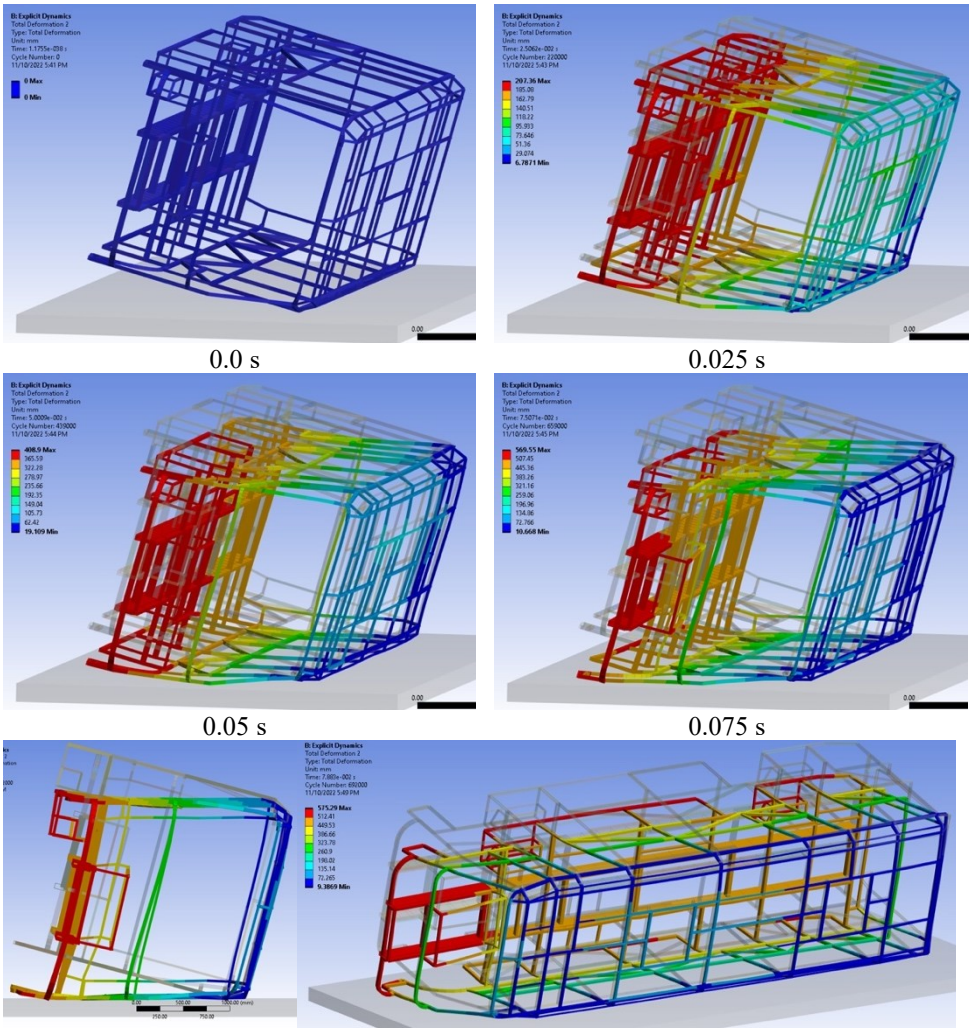


Fig. 5. TATA 079 body frame deformations under conditions of simulation tests for compliance with UN/ECE Regulation No. 66.

The correctness of the calculation can be judged on the basis of energy conversion graphs (total energy balance) - the mirror behaviour of the time distribution between Internal and Kinetic energy; absence of fluctuations in Hourglass energy, which depends on the state of the finite elements in the deformation process; general smoothness of conversion processes without unexpected jumps and breaks (fig.6).

How can you judge the safety of the structure in the conditions of tests for compliance with UN/ECE Regulation No. 66? It is necessary to check that no elements of the interior fall into the residual space which scheme is present on fig.7.

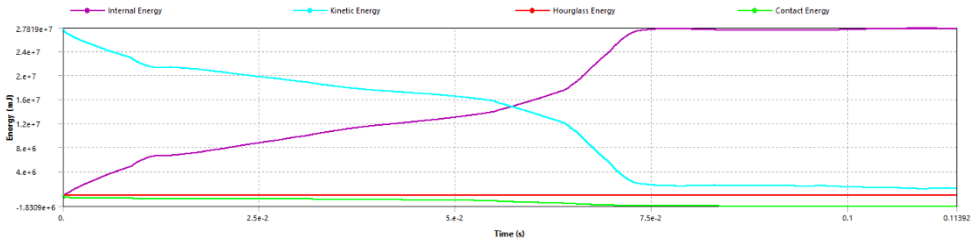


Fig.6. Energy conservation (Ansys Explicit Dynamics).

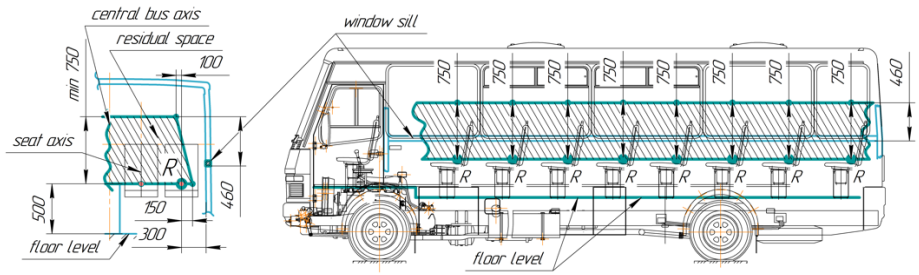


Fig.7. Scheme for determining the remaining space of the TATA 079 bus cabin.

4 Results convergence

According to Protocol No. 1036/S0/66-01/R/30-07 of certification tests, rollover of the bus was done from a special stand, height 805 mm, to the left side with an angular rotation speed of 5°/s by a crane on a truck chassis. Photo-results of rollovers are presented in Fig. 8.

Fig. 8. TATA 079 bus (BAZ-A079.23) tests in compliance with UN/ECE Regulation No. 66.

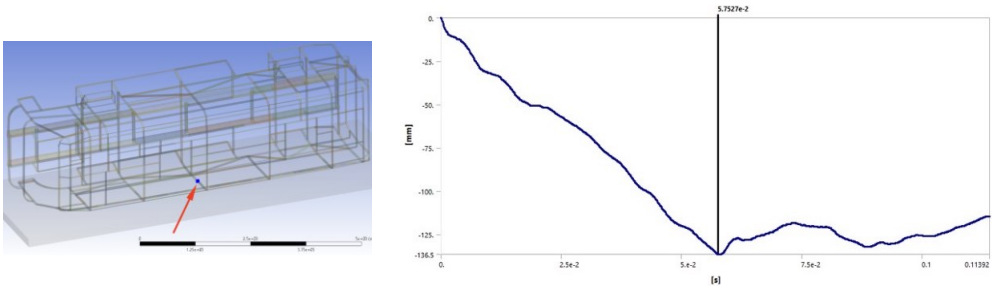
According to the signed protocol, during and after the rollovers, none of the displaced parts of the interior elements entered the residual space zone; none of the borders of the residual space were damaged by parts of the deformed body structure. The test results are presented in Table 1.

Let's analyse the results convergence of the experiment and the calculation based on the central rack #2 - the value of the actual deformation as a result of the real crash test was 135 mm (Table 2). We compare this result with the maximum recorded value on the graph of the

control point movement, which is located at a height of 460 mm relative to the window sill (Fig. 9): the calculated value is 136.5 mm (Fig. 9), which is within 1% of the error.

Table 2 – Natural test results of the TATA 079 (BAZ-A079.23) model in accordance with UN/ECE Regulation No. 66.

Numbers of the left side body racks	Permissible deformation, mm	Actual dynamic deformation, mm	Residual deformation, mm	Conclusion on compliance
1	2	3	4	5
Rack #1	350	178	80	Meets the req
Rack #2	350	135	65	Meets the req
Rack #3	350	74	40	Meets the req



a) b)

Fig. 9. Displacements of control point on rack #2: a) point locations on the model; b) displacements over time during the impact -136.5 mm is the max value.

5 Conclusions

1. The proposed methodology for bus bodies testing for compliance with UN/ECE Regulation No. 66 using modern modelling tools (Ansys Explicit Dynamics) demonstrated a high convergence of experimental and calculation results (within 1% error based on the selected window rack).
2. Besides the presented methodology demonstrates not only scientific value, but also significant economic efficiency in the development of new models of buses and certification of existing vehicles (crash test costs at least 200-250 k USD for buses of the smallest class and is not subject to restoration in the main costly part - its body).
3. Calculations are extremely time-consuming from the computing resources point of view, therefore it is advisable to further develop optimization measures for the effective formulation of boundary conditions that could ensure maximum identity to full-scale tests.
4. The suggested methodology is extremely relevant for the implementation of preventive measures to optimize the structure and strength of bodies in the early stages of design (before the stage of embodiment in metal) by engineering departments, plants, etc. The issue is not only the safety of future buses and their passing of certification, but also obtaining uniform strength of the body, reducing material consumption and improving the manufacturability by selecting more widespread profiles, optimizing constructive solutions, etc.

References

1. Holenko K.E., Krainyk L.V. Osoblyvosti formuvannia nesivnykh struktur karkasu avtobusa typu low-entry u Visnyku NU "Kharkivskyi politekhnichnyi instytut" 2008 r.- s. 152-157s.
2. K.E. Holenko, O.Z. Horbai, L.V. Krainyk "Kompiuterne modeliuvannia i analiz napruzheno-deformovanoho stanu karkasu kuzova avtobusa typu Low-entry" u Visnyku NU "Lvivska politekhnika". "Dynamika, mitsnist ta proektuvannia mashyn i pryladiv." 2008 r. № 614, s. 63 – 68
3. Holenko K. E. Otsinka totozhnosti modeliuvannia vidpovidnosti avtobusiv pravylu № 66 YeEK OON ta eksperymentalnykh vyprobuvan / K. E. Holenko, O. Z. Horbai, L. V. Krainyk // Visnyk Nats. tekhn. un-tu "KhPI" : zb. nauk. pr. Temat. vyp. : Avtomobile- ta traktorobuduvannia. – Kharkiv : NTU "KhPI". – 2010. – № 1. – S. 101-109.
4. Regulation No 66 of the Economic Commission for Europe of the United Nations (UN/ECE) — Uniform technical prescriptions concerning the approval of large passenger vehicles with regard to the strength of their superstructure (OJ L 321 06.12.2007, p. 55, ELI: https://op.europa.eu/en/publication-detail/-/publication/69a98949-88be-4e2a-bcb7-d26d4e8778b3)
5. Optymizatsiia struktury i mitsnosti avtobusnoho kuzova typu Low-entry: avtoref. dys. ... kand. tekhn. nauk : 05.22.02 / Holenko Kostiantyn Eduardovych ; Nats. un- t "Lviv. politekhnika". - L., 2011. - 20 s.
6. Kamarajan Balakrishnan, Arvind Sharma, Rajib Ali, Comparison of Explicit and Implicit Finite Element Methods and its Effectiveness for Drop Test of Electronic Control Unit, Procedia Engineering, Volume 173, 2017, Pages 424-431, ISSN 1877-7058, https://doi.org/10.1016/j.proeng.2016.12.042.
7. Ivan Rooij, R. (2011). Implicit versus explicit comparatives. In P. Égré, & N. Klinedinst (Eds.), Vagueness and language use (pp. 51-72). (Palgrave studies in pragmatics, language and cognition). Palgrave Macmillan. https://doi.org/10.1057/9780230299313_3
8. Brooks, L., Miller, A. (1979). A Comparison of Explicit and Implicit Knowledge of an Alphabet. In: Kolers, P.A., Wrolstad, M.E., Bouma, H. (eds) Processing of Visible Language. Nato Conference Series, vol 13. Springer, Boston, MA. https://doi.org/10.1007/978-1-4684-0994-9_24
9. Matolcsy, M. The severity of bus rollover accidents, Scientific Societyof Mechanical Engineers, Paper Number: 07 0989, Hungary. 2007. https://trid.trb.org/view/1367782
10. Özgün Küçük. "ROLLOVER CRASHWORTHINESS OF A MULTIPURPOSE COACH." (2014). https://www.academia.edu/12279444/Rollover_Crashworthiness_Of_A_Multipurpose_Coach