Improvement of the Energy Absorption Capacity of an Intercity Coach for Frontal Crash Accidents

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Abstract

According to the accident statistics for buses and coaches, accidents involving frontal crash constitute an important percentage among all bus accidents. In this type of accidents, front body of the bus structure gets severely damaged and this puts the driver and crew in great injury risk. And most of the frontal crash accidents result in death of the bus driver. Because of this, the safety of both the bus driver and the crew should be ensured in the case of frontal crash accidents. Providing the driver's safety is crucial since the driver is the key person for keeping the control of the bus in the event of an accident so that the safety of the passengers will be ensured.

Even though the most of the passive safety standards are related to the safety of the passengers, some international regulations exist for the driver's safety for heavy vehicles. The European regulation ECE-R29 is arranged to provide the safety of the truck cabin and the driver. This regulation involves a frontal crash pendulum test in which a plate with a specified mass strikes the cabin of the vehicle. A regulation specifically arranged for the safety of bus/coach in the case of frontal crashes does not exist, but some proposals similar to ECE-R29 are being discussed in Working Party on Passive Safety (GRSP) in United Nations Economic Commission for Europe (UNECE). Presumably, a similar regulation for buses will be imposed in the near future.

In this paper, frontal crash analysis of the structure of a bus front body was performed according to the ECE-R29 European regulation requirements and the strength of the bus structure was checked whether the safety requirements are satisfied. The nonlinear explicit finite element code LS-DYNA® was used for the crash analyses. The first stage of this study involves the frontal crash analyses of the baseline bus structure without any improvements. At this stage the weak parts of the front end structure of the bus body were determined. In the next stage some improvements were made on the bus structure in order to strengthen the front body. These modifications include the rearrangement of the weak profiles forming the bus front structure. Finally the modified bus structure was compared with the baseline model if the requirements for the driver's survival space were satisfied according to ECE-R29.

Keywords: *Crashworthiness, frontal crash, explicit dynamics, ECE R-29, LS-DYNA.*

1. INTRODUCTION

Bus and coach transportation constitutes an important proportion of the intercity passenger transportation especially in Turkey. Many people prefer traveling by bus for intercity transportation and this makes the security issues more crucial at the highroads. The passengers riding in the bus are in great risk if there is not enough protection of the bus driver during the course of an accident. When the accidents types investigated for buses and coaches, most of these accidents consist of rollover, frontal crash, side and rear collision. Among these types, the most encountered one after the rollover is the frontal crash accidents.

There are various statistical studies carried out related to bus and coach accidents in the literature. Enhanced Coach and Bus Occupant Safety (ECBOS) Project is one of these studies which includes the detailed statistical accident data for eight European countries [1]. Within the scope of the ECBOS project, the bus accidents occurred in Austria, France, Germany, Great Britain, Italy, Netherlands, Spain and Sweden were investigated in depth. In some of these countries, the percentage of the frontal crash accidents reaches up to 70 among all bus accident types. It was also stated in ECBOS Report that bus and coach transport is at least ten times safer than other road transports.

Another statistical accident analysis study was performed by Transport Canada [2]. In the final project report the research on accident statistics related to bus and coach passenger safety in Canada, USA and European countries was included in detail. It is concluded that each year approximately 20,000 bus and coach accidents happen and this value is the % 4 of the total road accidents and more than 35,000 people were injured in these accidents.

For a frontal crash accident involving busses, the person in great risk is the bus driver and the crew sitting next to the bus driver. Depending on the mass and the velocity of the bus, huge crash energies occur in the case of a frontal crash accident and this crash energy directly affects the bus driver and the crew. The passengers have the risk of injury if the driver gets injured during the accident. If the driver can keep the control of the bus in the event of an accident, the safety of the passengers could be ensured. Since it is a known fact that most of the frontal crash accidents result in the death of the bus driver, it is necessary to design passive safety systems for frontal crash accidents with an emphasis on the safety of the driver and the crew.

There are several regulations in the European community for passive safety of the vehicles. United Nations Economic Commission for Europe (UN-ECE) has regulations for passive safety which are compulsory for heavy vehicles. For instance, ECE R29 regulation arranges the frontal crash safety for trucks. There is currently no regulation related to frontal crash of buses and coaches similar to ECE R29. However this issue is being discussed in Working Party on Passive Safety (GRSP) in UNECE. In this study, ECE R29 regulation will be considered for the frontal crash safety of buses.

Beyond the statistical studies in the literature, there are many studies related to accident analysis. A detailed literature analysis was performed by Albertsson and Falkmer [3] to describe a pattern in bus and coach incident related injuries and fatalities. Raich [4] performed the safety analysis of a truck cabin according to ECE R29. In the related study, the truck cabin was numerically analyzed and tested. These analysis and tests included the frontal impact test, roof strength test and rear wall strength test. The survival space for the driver was also tried to be protected by optimizing the pedal box after the test.

Peter et al. [5] studied on the passive safety for the drivers and the couriers of coaches. They designed a crash unit in order to absorb the impact energy and increase the survival space for the driver and the courier. In that study, improvement in the frontal crashworthiness of coaches was developed and evaluated. Protection of bus drivers and bus passenger safety for frontal collisions were studied subsequently in the studies [6] and [7].

2. ECE R-29 REGULATION

The Finite Element Analysis for this study was based on ECE R29 international regulation. The regulation proposes an impacter plate which is made up of steel material and having a mass of 1500 ± 250 kg. This impacter has to be a rectangle with a width of 2500 mm and a height of 800 mm. The pendulum shall be freely suspended by two beams rigidly attached and spaced at least

1000 mm apart. The position of the pendulum plate should be so arranged that the vertical distance between the center of gravity of the pendulum plate and the R-point of the driver's seat is 50 mm below. According to the regulation the impact energy should be at least 45 kJ for the vehicles exceeding 7000 kg of mass. Under these conditions the driver's survival space should be checked after the test. For this purpose, a manikin should be used which is described in the regulation [8]. The fiftieth-percentile male body manikin is shown in Figure 1 [8].

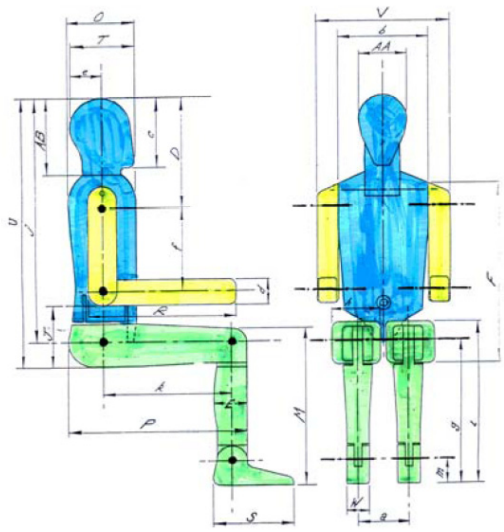

Figure 1. Manikin used in ECE R29 [8]

3. FINITE ELEMENT MODEL

The finite element analysis of this study was conducted by using explicit nonlinear finite element code LS-DYNA. The bus structure was crashed with a pendulum having a mass of 1500 kg as described in the ECE R29 regulation. The bus body consists of front body, front chassis, right and left side walls, roof, steering systems. The bus body and the seat structure were modeled in CATIA [9] and meshed in ANSA [10]. The overall bus finite element model consists of 467,999 nodes and 467,248 shell elements.

Considering the accuracy of the results and analysis time, the mesh size is chosen to be 10 mm for the places where there is not much deformation and a mesh size of 3 mm was selected for the critical parts that come into contact with the rigid impacter and have considerable deformation. Shell elements are modeled with 4-noded Belytschko-Lin-Tsay shell elements having five integration points through the thickness. Belytscko-Lin-Tsay shell element is chosen since it requires less mathematical calculations compared to other shell elements [11].

Two different material types were defined from the LS-DYNA material library (Type 20 and Type 24). Rigid material Type 20 was used to model the pendulum plate. Material Type 24 is an elasto-plastic material in which both the elastic and plastic regions can be included with true stress-true plastic strain curves. This material type was used for the whole bus structure. For the mild steel, Poisson's ratio, density and Young's modulus were taken to be 0.3, 7850 kg/m^3, 210 GPa, respectively. True stress and true plastic strain values for St 44 and Qste 460 mild steel are shown in Table 1 and Table 2, respectively. Strain rate effects were also included for the Material Model 24, where the constants C and P used in the Cowper-Symonds equation for the mild steel were 0.04 (ms)$^{-1}$ and 5, respectively, as in the previous studies [12,13].

Table 1. True stress-true plastic strain data points used for St 44 material

σ [MPa]	331.00	347.00	390.00	427.00	450.00	469.00	501.00	524.00	533.00
ε_p	0	0.018	0.037	0.056	0.075	0.093	0.138	0.180	0.230

Table 2. True stress-true plastic strain data points used for Qste 460 material

σ [MPa]	456.84	499.99	529.79	548.89	560.27	571.19	595.56	616.37	645.35	650.25
ε_p	0	0.002	0.004	0.008	0.015	0.025	0.050	0.077	0.127	0.146

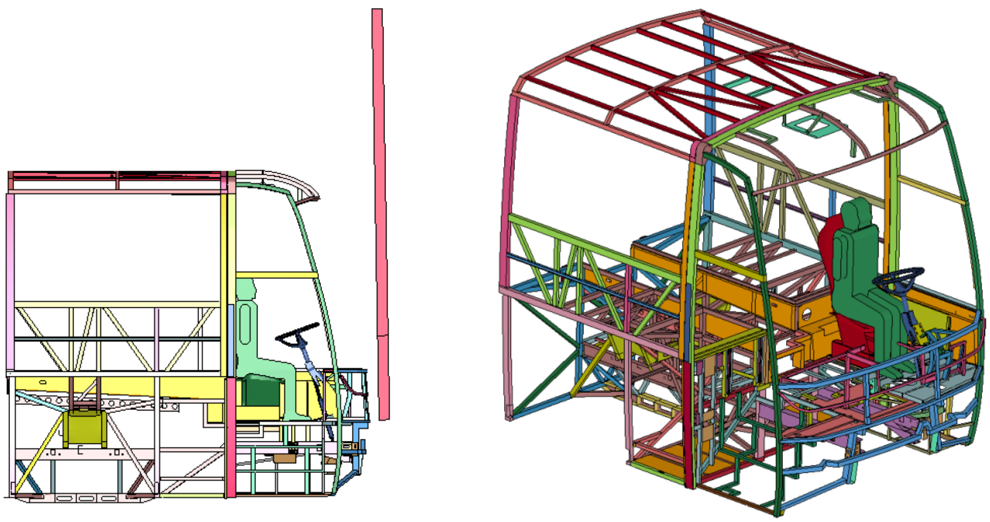

Figure 2. The bus structure and the manikin.

‘‘AUTOMATIC_SINGLE_SURFACE” contact was defined for the contact algorithm between the parts of the bus structure and the self contact of each part. The reason for using the automatic contact definition is that it is usually difficult to estimate how and where the contact will take place because of the large deformations occurring during the crash incidence. “AUTOMATIC_SURFACE_TO_SURFACE” contact was used to define the contact between the pendulum and the bus. For both of the contact definitions the static and dynamic friction coefficients for the deformable parts were taken to be 0.3 and 0.2, respectively.

The mass moment of inertia of the pendulum should be calculated and the angular velocity of the pendulum should be defined so as to provide the desired impact energy. The pendulum size and dimensions are taken from ECE R29 and will be used in the crash analysis. It has a width of 2500 mm and a height of 800 mm. The total mass of the pendulum plate is 1500 kg. The length of the pendulum arm which is the distance between the axis of rotation and the center of gravity of the pendulum plate is at 3500 mm as seen Figure 3. By using these dimensions and mass of the pendulum, the inertial parameters of the pendulum can be calculated and used in LS-DYNA inertia card.

According to ECE R-29 regulation the desired kinetic energy of the pendulum is 45 kJ. This energy is given to the system as a kinetic energy. The desired angular velocity of the pendulum can be calculated by Equation 1, in order to obtain the required kinetic energy. The mass moment inertia of the pendulum plate about y-axis (see Figure 3) can be calculated by Equation 2.

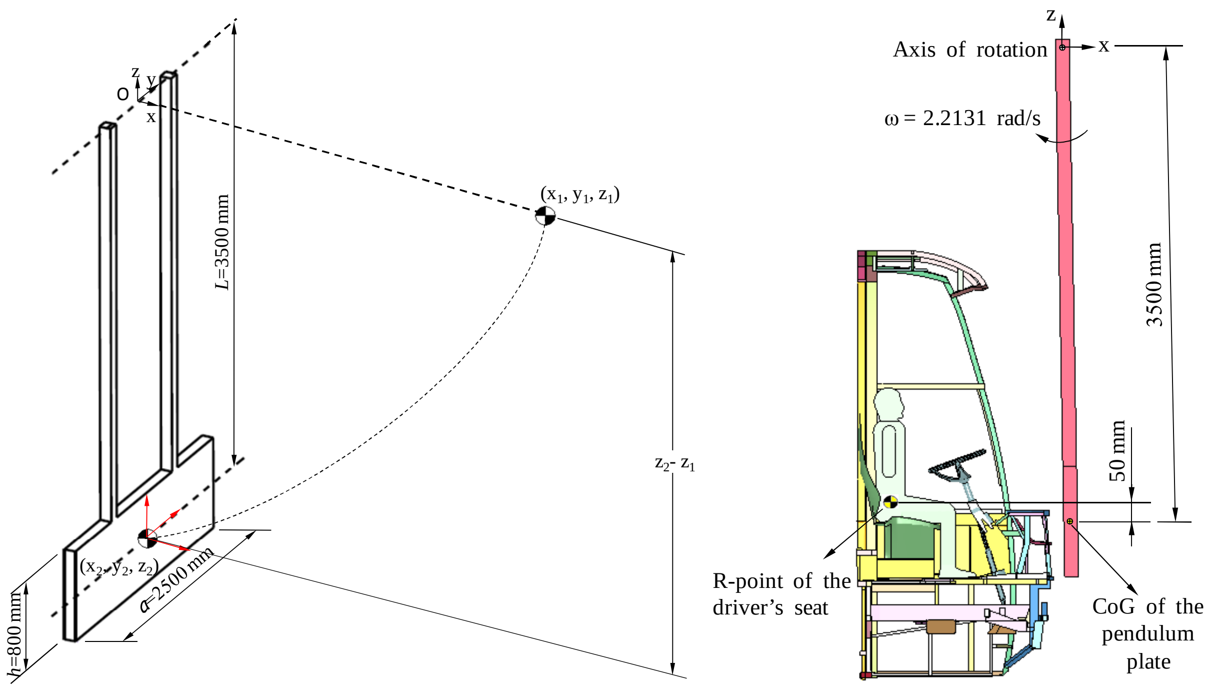

Figure 3. Dimensions of the pendulum plate and the position with respect to R-Point

$$E = \frac{1}{2} I_{yy} \omega_y^{\ 2} \tag{1}$$

$$I_{yy} = I_{y_c y_c} + mL^2 \tag{2}$$

The angular velocity of the pendulum was found to be ω = 2.2131 rad/s. "PART_INERTIA" card was used to define the mass moment of inertia of the pendulum. In this card the mass, mass moment of inertia and angular velocity of the pendulum were defined. Here it should be noted that, the pendulum arms are not included in the mass and inertia calculations.

4. ANALYSIS RESULTS

The crash simulations were performed for the baseline bus structure and the bus structure with two different energy absorber designs. This two absorber designs can be seen in Figure 4. Design 1 consists of conical energy absorbers which were taken from a previous parametric study [14] and Design 2 is the other bus structure with several corrugated crash boxes. Additionally, the present bus body structure was strengthened by adding some new structures and increasing the necessary wall thicknesses of some tubes in front body.

The baseline model which is the present bus structure without any changes made was analyzed first. After this simulation the weak regions of the bus structure were determined. It was also seen that with its current condition, the baseline model does not satisfy the ECE R29 requirements for frontal collision. It was seen that the weak regions include especially the profiles which supports the driver subpanel. These profiles are crucial in the sense that they are subjected to axial impact when the pendulum strikes the front body. Finite element analyses showed that these profiles were not strong enough to resist the impact energy.

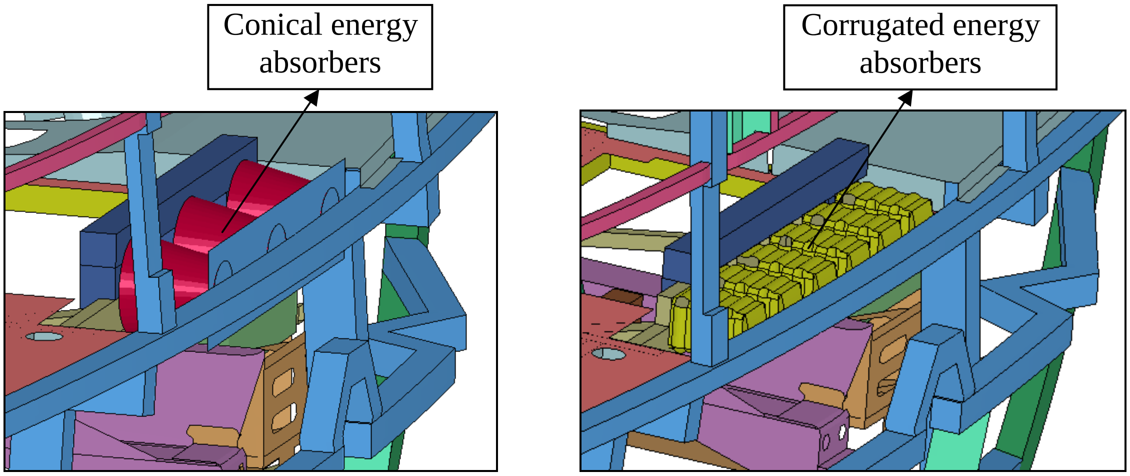

Figure 4. Design 1 and Design 2

The global buckling is an undesired situation for energy absorbers since it reduces the energy absorption capacity. In order to prevent global buckling of these profiles, a new design was made. This design was assembled to the bus structure so that the global buckling was prevented. With this new design, the resistance to axial impact was increased. This design change directly affected the amount of intrusion to the driver's survival space in a positive manner.

Besides the new designs, some small design changes made to the present bus structure which included adding additional profiles to critical regions and changing the wall thicknesses of some of the profiles. With these initial modifications, it was seen that a good improvement was obtained in the crash energy absorption without adding extra energy absorber geometries to the bus structure.

After the modifications in the present bus structure, some energy absorber designs were made and assembled to the bus front body. As mentioned earlier, these absorber designs consist of two different absorber geometries. In the first design which is called 'Design 1', three conical absorbers having a semi-apical angle of 12.5° were used. In the second design, the energy absorbers were constructed by using corrugated plates.

Three models namely; baseline model, Design 1 and Design 2, were analyzed and the results of these analyses is shown in Figure 5. In this figure the progressive deformation of the three different bus structure can be seen with respect to the manikin. It can be deducted from these figures that while the baseline bus structure was not successful in preventing the steering wheel penetrating the survival space of the driver, the other two designs provided enough clearance so that there were no intrusions experienced.

Kinetic energy, internal energy, sliding energy and hourglass energy graphs can be seen in Figure 6, for the baseline model. From this figure, it can be deducted that the accuracy criteria is ensured since the total energy remained constant and the hourglass energy did not exceed the %10 of the internal energy.

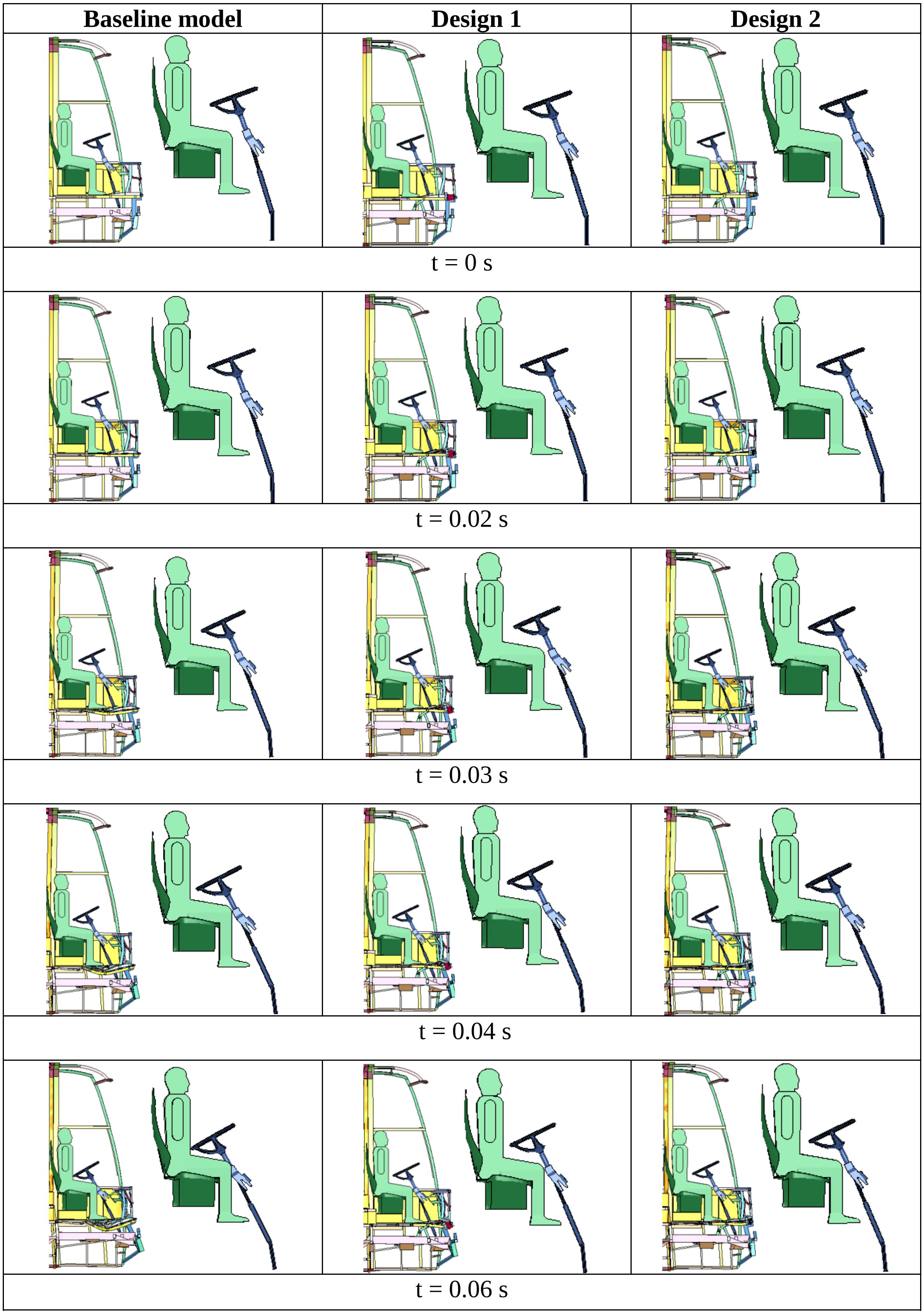

Figure 5. Progressive deformation of the steering system with respect to the manikin.

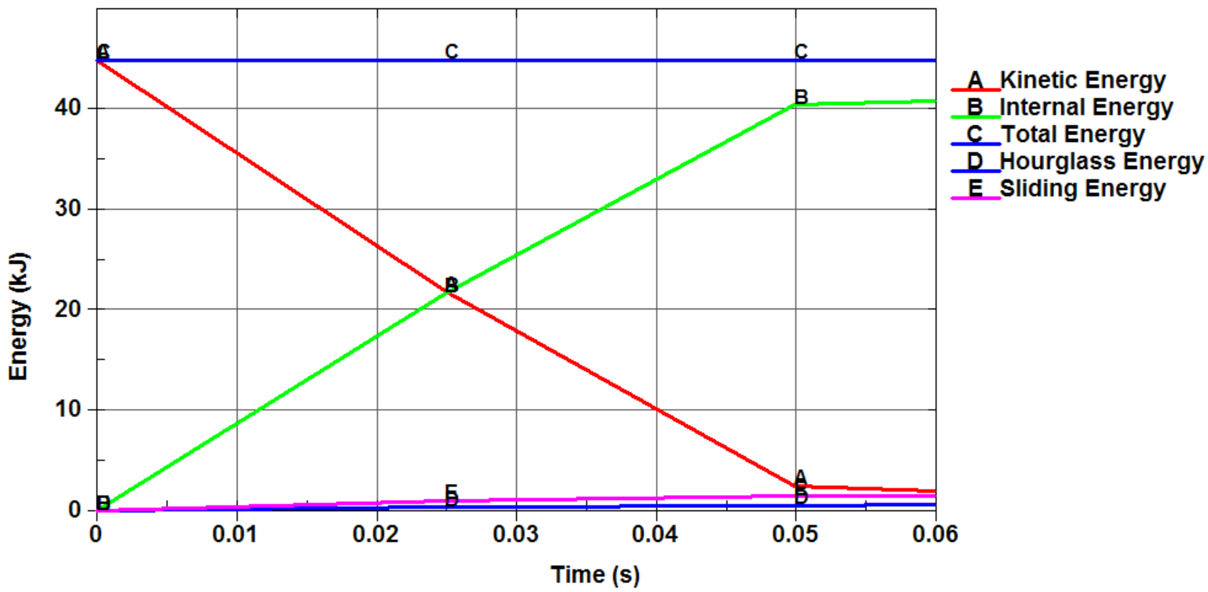

Figure 6. Energy graphs for the baseline bus structure.

5. CONCLUSIONS

The baseline design was tested numerically based on ECE R29 regulations for truck cabins. The reason behind this is that there are no regulations yet for the safety of the driver and the crew in case of frontal collision. The pendulum test was numerically conducted and it was seen that the baseline design does not satisfied the requirements for ECE R29. Some modifications have been adopted and two new designs have been made in order to satisfy the requirements. Global buckling was observed on some of the axial profiles in the direction of crush during the impact which was the main reason for the penetration to the survival space. The stiffness of these profiles was increased by some design changes in order to prevent buckling. Some weak parts of the front body were strengthened by making the thicknesses thicker or with some modifications. Along with these improvements in the structure of the front body, two different designs were adopted to the structure. In both models there were no intrusions observed.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] ECBOS-Enhanced Coach and Bus Occupant Safety Summary Report, UNECE Informal Document: GRSG 86-4,2004.
[2] "Evaluation of Occupant Protection in Busses", Rona Kinetics and Associates Ltd., North Vancauver, BC, Canada, Report RK02-06, 2002
[3] P. Albertsson, T. Falkmer, T. (2005) 'Is there a pattern in European bus and coach incidents? A literature analysis with special focus on injury causation and injury mechanisms', *Accident Analysis and Prevention*, 37 (2) (2005), pp.225–233.
[4] H. Raich, "Safety analysis of the new actros megaspace cabin according to ECE-R29/02", 4th European LS-DYNA Users Conference, 2003.
[5] Peter de Coo, Rene Hazelebach, Eric van Oorschot, Jaap Wessels, "Improved safety for drivers and couriers of coaches" In: Paper Presented at the Proceedings of the 17th International Technical Conference on the Enhanced Safety of Vehicles, Amsterdam, the Netherlands, 2001.
[6] S. Okano, F. Mitsuishi, Y. Sukegawa, F. Matsukawa, "Research on bus passenger safety in frontal impacts" In: Paper Presented at the Proceedings of the 17th International Technical Conference on the Enhanced Safety of Vehicles, Amsterdam, the Netherlands, 2001.
[7] Matolcsy M. "Protection of bus drivers in frontal collisions" In: Paper Presented at the Proceedings of the 18th International Technical Conference on the Enhanced Safety of Vehicles, Nagoya, Japan, 2003
[8] "Driver and crew prection in frontal colllision of buses", UNECE Informal Document: GRSG 96-19, 4-8 May 2009.
[9] CATIA, Dassault Systèmes of America Corp., 6320 Canoga Avenue – Trillium, East Tower, Woodlands Hills, CA 91367, USA. <www.3ds.com>.
[10] ANSA BETA-CAE Systems, User's Guide, Thessaloniki, Greece, 2008.
[11] LS-DYNA Keyword User's Manual, Livermore Software Technology Corporation: Livermore, California; May, 1999.
[12] B. Wang, G. Lu, "Mushrooming of circular tubes under dynamic axial loading", Thin-Walled Struct., 40 (2002), pp. 167-182.
[13] G. Lu, T. Yu, "Energy absorption of structures and materials", NW Boca Raton FL 33431, CRC Press LLC, USA, 2003.
[14] M. A. Guler, M.E. Cerit, B. Bayram, B. Gerçeker, E. Karakaya, "The effect of geometrical parameters on the energy absorption characteristics of thin-walled structures under axial impact loading", International Journal of Crashworthiness, in press.