

Improving the Roadside Safety with Computational Simulations

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ABSTRACT

The road restraint systems on public streets are used to prevent a vehicle to veer off the road or its breakthrough to the opposite side of the road. The road restraint systems designed according to the EN 1317 standard are intended to provide certifiable levels of vehicle containment, to redirect errant vehicles and to provide guidance for pedestrians and other road users. Its proper design is therefore crucially important for safety of all road users.

Practical observations of installed systems indicate that the current design of road restraint system is far too stiff. This results in unacceptable decelerations during the vehicle impact. The global stiffness of the road restraint system is largely attributed to the design of the distance spacer in the initial phase of an impact.

The purpose of this research is to evaluate several new designs of a distance spacer with increased strain energy absorption due to controlled deformation during the vehicle impact. The impact severity and stiffness of various designs have been evaluated with dynamic nonlinear elasto-plastic analysis of a three-dimensional road restraint system within the framework of the finite element method with LS-DYNA.

The computational analyses prove that the currently used distance spacer is indeed too stiff and that new designs assure controllable elasto-plastic deformation and crash energy absorption which in turn decreases the decelerations of an impact vehicle and consequently increases the safety of vehicle passengers.

INTRODUCTION

To assure adequate safety level is one of the major problems in road transportation. To maintain and improve roadside safety it is necessary to install certain devices to restrain vehicles and pedestrians from entering dangerous areas. The road restraint systems designed according to the European EN 1317 standard provide certain levels of vehicle containment, redirect errant vehicles and provide guidance for pedestrians and other road users.



Figure 1 Currently used road restraint system in Slovenia

To provide appropriate safety levels for vehicle passengers the safety barriers should be designed to absorb as much impact energy as possible in the case of vehicle impact and at the same time maintain their integrity. Practical observations of installed systems along Slovenian's highways, which have not changed much in the several past decades, indicate that the current design (Figure 1) of the road restraint system is too stiff, especially in the initial phase of an impact, which results in unacceptable decelerations during vehicle impact. This high stiffness is largely attributed to the current design of the distance spacer. By adopting the European transportation

legislation, it is necessary to reevaluate the safety barriers and propose certain design changes. This requirement prompted a new research into ways how to reduce the stiffness of the road restraint system with a new distance spacer design with increased crash energy absorption during vehicle impact.

Behavior of four different distance spacer designs under test vehicle impact conditions has been analyzed with dynamic nonlinear finite element code LS-DYNA.

BASIC DESIGN REQUIREMENTS

Safety barriers are subjected to large impacting forces which are applied very rapidly. Important barrier installation considerations are type of the guardrail, installation height, distance spacers, proper post spacing and guardrail length. The barriers are usually made of steel, although higher containment levels can sometimes be achieved only by using concrete blocks.

The steel road restraint systems generally comprise of the following parts (Figure 2):

- the guardrail: usually W-shaped segments, which are longitudinally connected by bolts; they are deformable and reduce the severity of an impact but should be strong enough to prevent rupturing in any case;
- the supporting sheet metal: gives the former an additional support;
- the distance spacer: decreases the impact severity and connects the guardrail with the post;
- the post: carries the distance spacer and/or the guardrail and assures the guardrail position at certain distance from and above the road respectively.

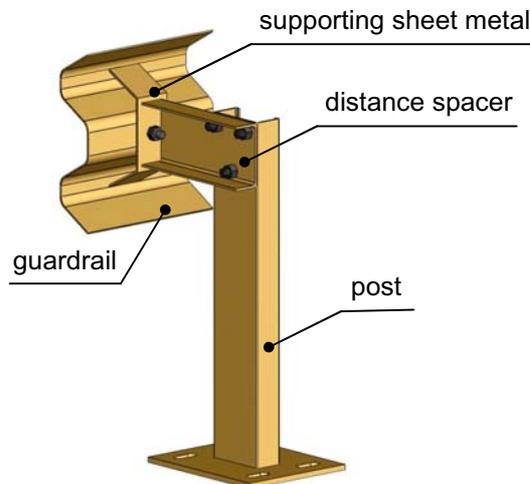


Figure 2 Elements of the road restraint system

Road safety barriers can be one- or two-sided, with a distance spacer or without it, depending on type of the road, traffic flow density and available space. Distance spacers are usually used on highways and other road restraint systems with high speed traffic. Guardrails without distance spacers are often used in places where the space for their installation is limited.

SPECIFICATIONS ACCORDING TO EN 1317

Road restraint systems on public roads in the European Union have to fulfill the EN 1317 standard in terms of the vehicle containment level, the level of expected vehicle occupant decelerations during impact and the consequent system deformation. The standard prescribes exact criteria which the road restraint system has to fulfill under specific impact conditions.

There are many different parameters that have to be taken into account when a vehicle collides with a guardrail: vehicle velocity (v), vehicle mass (m), impact angle (α), type and behavior of a vehicle, road conditions and the deformation of the road restraint system (W). Some of these parameters are shown on figure 3.

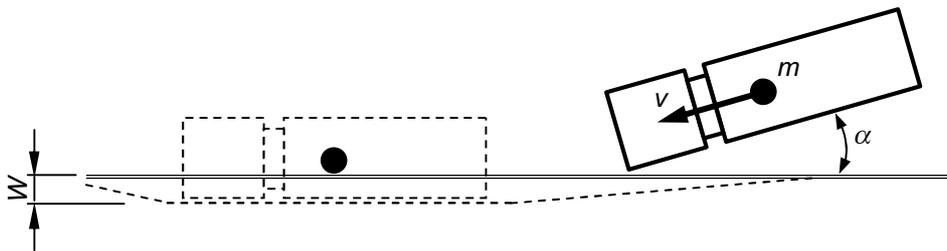


Figure 3 Parameters of vehicle impact against safety barrier

The safety barrier has to sustain impact of different vehicle types (from passenger cars to trucks or buses) under different impact conditions regarding the vehicle velocity, impact angle and road conditions. In case of a lower-weight vehicle impact (passenger car), the restraint system should have the ability to deform, so that the kinetic energy of an impact is absorbed mostly by the restraint system and vehicle deformation. This significantly reduces deceleration levels experienced by vehicle occupants and increases their safety. However, in a case of a higher-weight vehicle impact (truck, bus), the system should maintain its integrity to contain and deflect the vehicle on the road. Thus, the barrier design is a compromise between its stiffness (deformability) and strength.

Road restraint systems according to EN 1317-2 have to fulfill the following criteria:

- Containment level - represents the level of containment for different types of vehicles. The levels depend on type of the road and the average daily traffic per year. The standard defines four levels of containment: low containment level (T1, T2 and T3), normal containment level (N1 and N2), high containment level (H1, H2 and H3) and very high containment level (H4a and H4b). For each containment level the standard prescribes exact impact conditions (weight, velocity and impact angle of a vehicle), which the barrier has to sustain in case of an impact.
- Impact severity – a measure of impact consequences of an with regard to passengers. Three measures are used: the acceleration severity index (ASI), the theoretical head impact velocity (THIV) and the post-impact head deceleration (PHD). According to the standard the limit values of these parameters are: ASI = 1,0 (1,4), THIV = 33 km/h and PHD = 20 g.
- Deformation of the restraint system – a working width of the barrier, which is a distance between the side of the W-beam facing the traffic before the impact and the maximum lateral position of any major part of the system after the impact (Figure 3). There are eight classes of deformation of the restraint system (W1 ... W8). Deformation is measured in meters.

THE DISTANCE SPACER DESIGN

The evaluated road restraint system is made of construction steel S 235 (St 37-2 according to DIN). The W-shaped guardrail is made of 3 mm thick metal sheet, with improved strength characteristics. The usual length of the W-segment is 4,2 m; where the splice length is equal to 200 mm. Supporting sheet metal is 6 mm thick and is welded to the distance spacer. The currently used distance spacer is U-shaped with dimensions 120 mm x 50 mm and 260 mm in length. The thickness of the distance spacer is 4 mm. The post is C-shaped with dimensions 55 mm x 120 mm x 4 mm and is approximately 2 m long. The distance between posts depends on the required containment level and can be equal to 1,33 m (higher containment level), 2 m or 4 m (lower containment level). Posts are always oriented with the closed profile face towards the traffic flow direction. If a post cannot be rammed into the soil, because of the rock or any other obstacles, it has to be fixed with an anchor-plate. W-beams, posts and distance spacers are joined with screws M16 x 35 mm of strength class 5.8.

The distance spacer has to be designed in such a way that the road restraint system geometrically suits the national technical regulations. In case of an impact, it should deform in a controlled manner, thus absorbing as much kinetic energy as possible through plastic deformation. The distance spacer must break from the W-beam or the post during and after an impact. It also has to be easy and cheap to produce, simple enough to assemble and allow for permanent and simple maintenance.

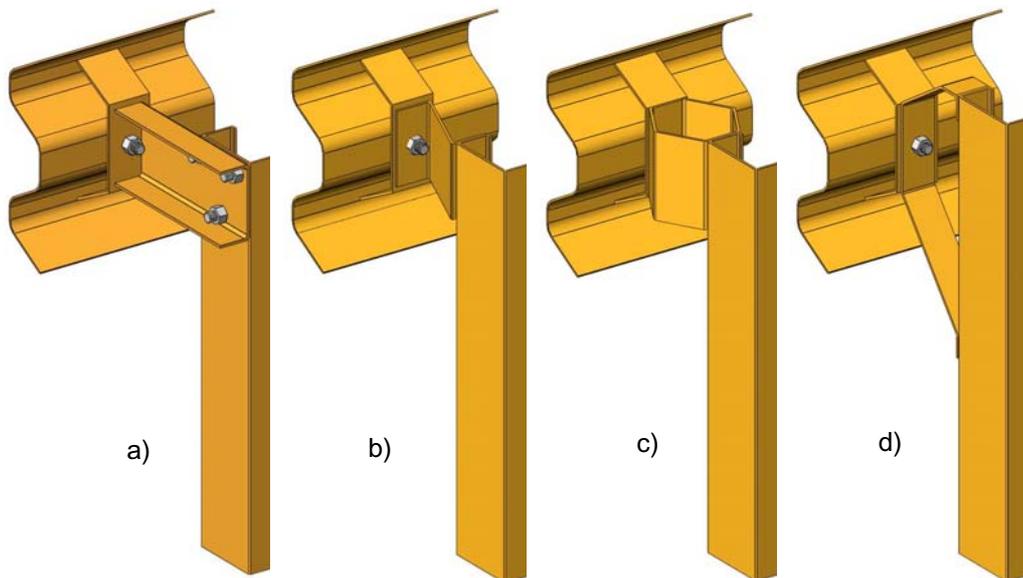


Figure 4 Different shapes of distance spacers:
a - U-shaped (current); b - Z-shaped; c - hexagonal shaped; d - D-shaped

Suitability of three new distance spacers (Figure 4) has been investigated and compared with the existing design. Parametric computational analyses in the framework of nonlinear dynamic finite element analysis have been performed for the purpose of determining the best distance spacer design that fulfills all design requirements.

DESCRIPTION OF THE COMPUTATIONAL MODEL

ETA Femb PC 27.0 was used for the generation of the geometry and the finite element mesh and for definition of material models and boundary conditions. The basic geometry was modeled by using the MSC.visualNastran for Windows.

Discretised model

A 20-meter long segment of the road restraint system was found to be sufficient for impact analyses. The guardrail was modeled as a continuous element under presumption that the guardrail splices were not the weakest link, according to [2]. The model comprised of 10 posts, supporting metal sheets and distance spacers spaced at a 2 m distance. All component parts were modeled with the 4-node Belytschko-Tsay shell elements with three integration points through the shell thickness. The average size of the shell elements was 10 mm. The impacting vehicle was approximated with a rigid bumper, weighing 900 kg, the position and geometry of which corresponded to that of a real car. The bumper was modeled with rigid shell elements. The whole model consisted of approximately 42500 nodes and 40500 elements.

Material model

All parts of the road restraint system are made of the construction steel S 235. Standard tensile tests of different thickness specimens were carried out according to the standard DIN 50 115 to obtain realistic material properties of analyzed road restraint elements in terms of their Young's modulus, yield stress, elasto-plastic relationship and ultimate strength (Table 1).

Table 1 Physical properties of sheet metals of road restraint system

Sheet metal thickness	Young's modulus	Poisson ratio	Yield stress	Plasticity modulus	Tensile strength
[mm]	[MPa]	/	[MPa]	[MPa]	[MPa]
3	190000	0,29	285	696	400
4	200000	0,29	330	969	450
6	210000	0,29	380	1200	480

Obtained material parameters were used to define elastic-plastic material model (Type 3) in subsequent computational analyses with isotropic hardening. It was presumed that the bumper, bolts and welds were non-deformable bodies and were therefore assigned as the rigid material model (Type 20).

The level of effective plastic strain was used as a failure condition. The maximum effective strain was set to 0,28 which corresponds to 28% ductility of S 235 steel. When the effective plastic strain reached that value, the element load carrying capability (stress) was reduced to zero, effectively removing the element from the model. If the force in the bolt connection exceeded the failure force (normal force - $S_N = 75,2$ kN and shear force $S_S = 37,6$ kN) the bolt connection was also removed from the model.

The posts were fixed at the lower part at edge 1 (Figure 5). The continuation of the guardrail was simulated by the linear springs that were attached to both ends of the guardrail - edge 2 (Figure 5). The stiffness of the springs was set to 520 N/mm. All surfaces of the model were defined as a single surface contact model, thus effectively accounting for multiple self-contacting regimes during computational impact analyses. The static and dynamic friction between all parts was set to 0,1 and 0,05, respectively.

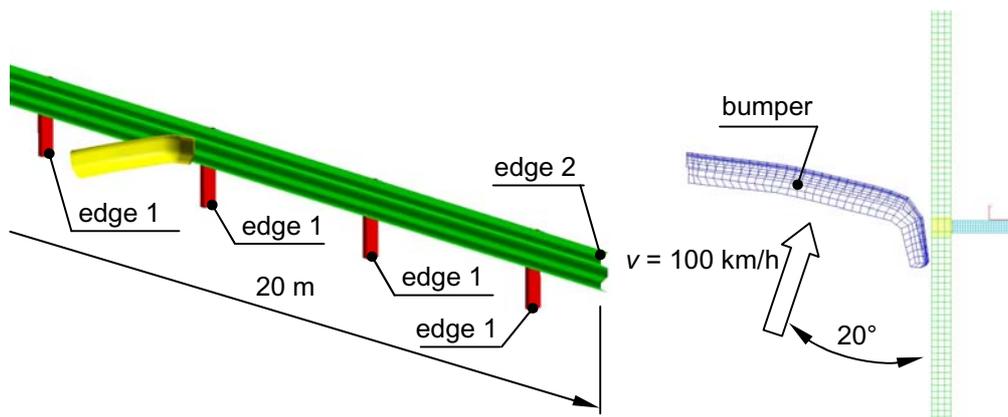


Figure 5 Boundary conditions

Dynamic model properties

The bumper was prescribed to have the initial velocity of 100 km/h at the impact angle of 20° with regard to the guardrail (Figure 5). The kinetic energy of the system was 350 kJ. The analysis time interval was set to 450 ms. The required results output interval was set to 0,1 ms. The time step for explicit transient dynamic analysis was automatically set by LS-DYNA to 1,4 μs with regard to the lowest resonant frequency of the structure. The analyses run approximately 85-95 hours on a PowerPC with 2 AMD 2000+ MHz processors and 2 GB RAM, depending on the complexity of the individual model.

ANALYSIS OF COMPUTATIONAL RESULTS

For the post-processing Eta/PostGL was applied for the visualization of the results and eta/PostGL Graph for numerical validation of results and preparation of graphs.

The results of computational simulations are shown in the figure 6. It is obvious that the current distance spacer is very stiff and does not absorb any crash energy. The Z-shaped distance spacer does not provide enough resistance against impact forces and deforms very quickly, pushing the guardrail to the post. Because of its asymmetric shape its deformation is also less predictable. The hexagonal distance spacer achieved the best results. It deformed in a controllable manner until the guardrail was pushed to the post and assured higher resistance to the loading than the Z-shaped distance spacer. The D-shaped distance spacer has achieved the worst results among newly designed distance spacers. Its single major advantage is the fact that it

pushes the guardrail up in the case of an impact which prevents the vehicle from overrunning the guardrail. In our case however, the bumper underrun the guardrail, which is not realistic. Therefore the computational results of the road restraint system with the D-shaped distance spacer are not relevant after the time of first underrun, which is 170 ms.

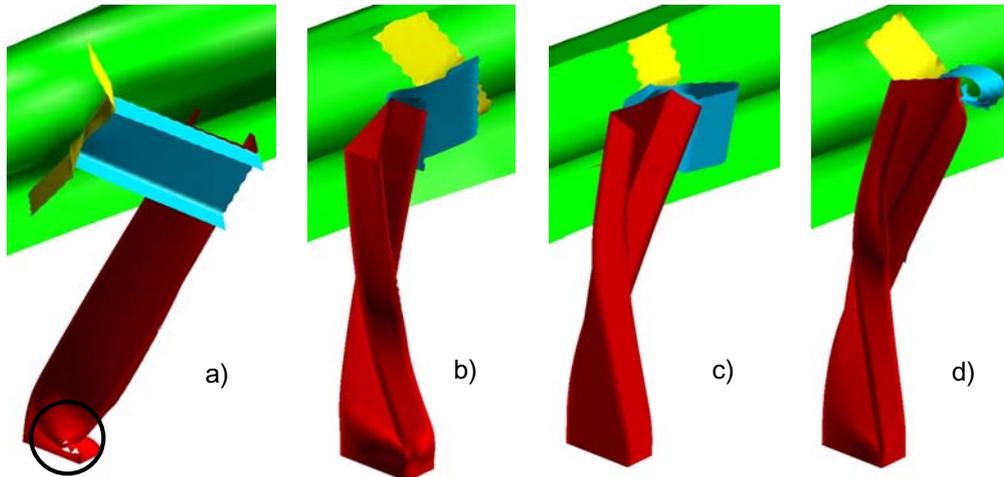


Figure 6 Deformation of road restraint system under applied load:
 a – U-shaped (current); b – Z-shaped; c – hexagonal shaped; d – D-shaped

Figure 6a shows that the effective plastic strain has reached the limit value and caused the material failure at the lower part of the post. Strain values have also exceeded the limit values in bolt connections between the guardrail and the supporting sheet metal, effectively severing the connection between guardrail and the post. Practical observations of past accidents confirm these computational predictions. The design evaluation data were the following: working width (W), contact length of a vehicle along the road restraint system (l), impact decelerations and crash energy absorption. The working width and contact length are given in table 2. The absorbed crash energy is illustrated in figure 7. The results clearly show that the current distance spacer absorbed the lowest amount of crash energy and that the best performance was demonstrated by the hexagonal distance spacer.

Table 2 Deformation of the road restraint system

Distance spacer	Working width	Contact length along the road restraint system
	[m]	[m]
U-shaped	8,25	11,7
Z-shaped	7,10	13,2
Hexagonal shaped	7,80	14,2
D-shaped	6,00	/

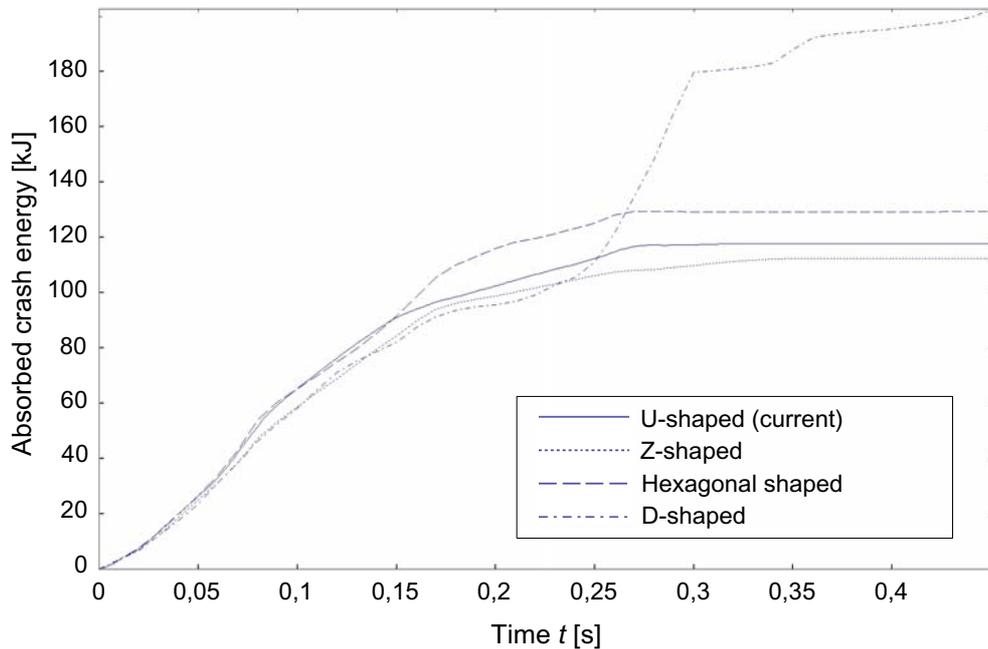


Figure 7 Absorbed crash energy during impact at the road restraint system

Vehicle deceleration during the impact is shown in the figure 8. The extreme values appear in two groups: when the vehicle first contacts the guardrail (first extremes group) and when the vehicle reaches the first post (second extremes group). The deceleration extremes corresponding to different distance spacers are slightly apart due to an impacting bumper velocity difference after the vehicle impact. The figure shows that the decelerations, experienced by the bumper impacting into a barrier

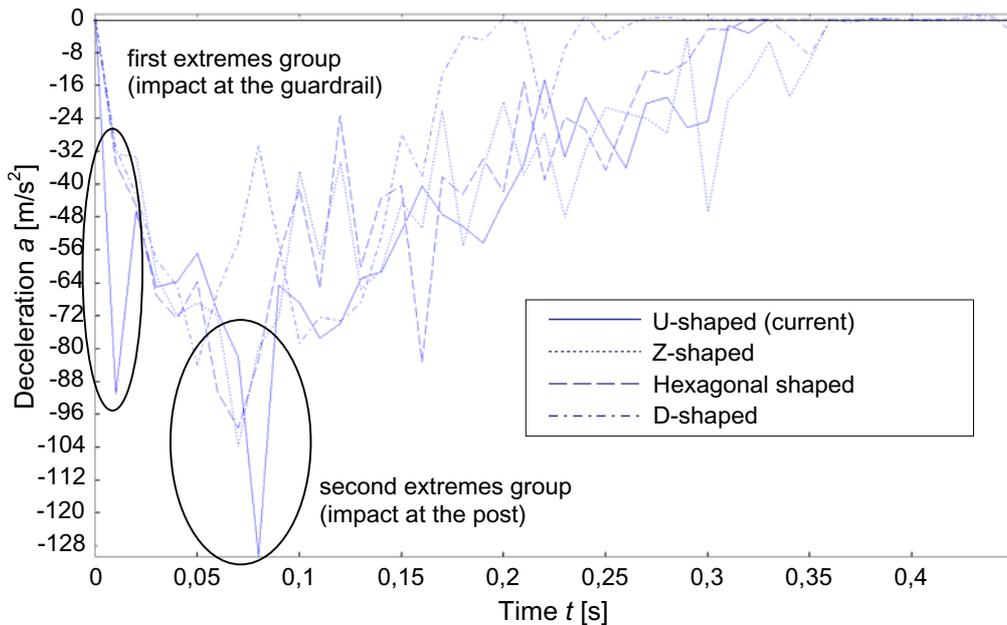


Figure 8 Lateral vehicle deceleration during impact at the road restraint system

with the current distance spacer, reach the maximum value at the time of an impact into the guardrail. Because of the highest deceleration at the vehicle impact, the bumper reaches the post as last where it also reaches the maximum deceleration. It is evident that the distance spacer has significant influence on the behavior of the road restraint system in the initial phase of an impact where it acts as an efficient energy absorber. Results comparison shows that with a better distance spacer design it is possible to reduce deceleration in this phase of an impact by more than three times.

The comparison of results shows that the current distance spacer does not satisfy all the design requirements. By means of the computational analysis it was proven that the new distance spacer designs can achieve better crash energy absorption and consequently lower the decelerations which the vehicle passengers have to withstand during the impact.

The impact severity index (ASI) is a measure of the vehicle motion severity for the passengers and was calculated according to the EN 1317. ASI is defined as:

$$ASI(t) = \sqrt{\left(\frac{\bar{a}_{normal}}{\hat{a}_{normal}}\right)^2 + \left(\frac{\bar{a}_{lateral}}{\hat{a}_{lateral}}\right)^2} < 1$$

where $\bar{a}_{normal} = 12g$, $\bar{a}_{lateral} = 9g$ are limit values of the acceleration and \hat{a}_{normal} , $\hat{a}_{lateral}$ are the components of the acceleration of the vehicle, averaged over a moving time interval of $\delta = 50$ ms.

If computed ASI value is higher than 1, then the consequences of an impact are too dangerous or even lethal for the passengers. As it is clear from the figure 9, the ASI index for tested systems does not exceed the limiting value in any case. The highest value of 0,81 was obtained for the currently used distance spacer.

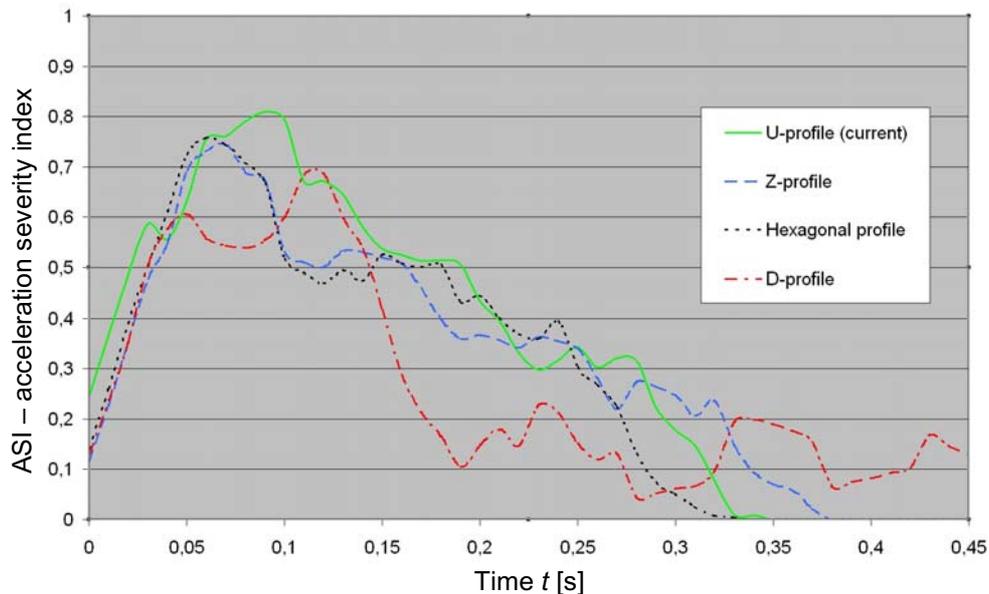


Figure 9 Acceleration severity index for road restraint systems with various distance spacers

CONCLUSION

Computational dynamic nonlinear finite element analysis was used for design evaluation of different distance spacers of the road restraint system subjected to vehicle impact.

The results of computational analyses prove that it is possible to minimize the stiffness of the road restraint system and maximize the energy absorption ability of the system with new distance spacer designs. It is obvious that the current distance spacer was designed only according to the geometrical rules, regardless of its functionality. The best results were achieved by the hexagonal distance spacer, which provides the highest level of crash energy absorption. The geometry of the hexagonal distance spacer assures controllable deformation and is not sensitive to the impact angle of a vehicle due to its symmetry.

The next phase of this research is simulation of a real vehicle impact into the road restraint system (Figure 10), accounting also for the soil deformation.



Figure 10 Simulation of road restraint system subjected to test vehicle impact

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