LS-DYNA simulations of the impacts of a 38-ton Heavy Goods Vehicle into a road cable barrier

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1 Introduction

Nowadays, more and more attention is being paid to safety on roads and motorways. It is due to the continuous development of road and motorway network and a significant increase of the number of vehicles on roads. To meet the expectations of improving road safety in Poland, the Road Innovations Development (RID) research programme was implemented in 2016. The aim of the RID 3A - Road Safety Equipment (*RoSE*) project is a comprehensive analysis of various road restraint systems and various types of road safety equipment installed on roads and bridges. The RID 3B - Effect of time and operating conditions of the durability and functionality of the elements of road safety (*LifeRoSE*) complementary project is aimed at developing innovative and comprehensive road management methodology for road safety equipment and traffic management measures. Part of the aforementioned projects is a thorough study of safety barriers based, among others, on full-scale crash tests and a number of numerical simulations using LS-DYNA.
The aim of the paper is to assess the crashworthiness of a road cable barrier during an impact of a Heavy Goods Vehicle (HGV) weighing 38 tons. A numerical model of the safety device was developed and validated with a full-scale crash test. Based on this computational model, a series of virtual crash tests were carried out in which the HGV collides with the barrier under various impact conditions. Some of the cases will be compared with real accident outcome that took place on highway in Poland.

2 RID 3A and RID 3B projects

The main objective of the *RoSE* project is to perform a complex set of research tasks of functionality of different road restraint systems described in PN-EN 1317 standard and supporting structures defined in PN-EN 12767 standard installed on roads and bridges. As part of the project, a wide analysis of guidelines concerning road safety equipment in Poland, Europe (28 countries) and in 9 countries outside Europe was carried out. For the purpose of the project, 9 full-scale crash tests and approx. 390 numerical simulations of crash tests were conducted. Based on the aforementioned tasks, an extensive analysis of all the gathered data was performed. The aim of the project is to develop a method for selecting the best type of road safety equipment for different road types, road hazards, traffic mixture, traffic conditions and for developing suggestions and recommendations for new guidelines in Poland.
The aim of the *LifeRoSE* project is to develop road management methodology for road safety measures with regard to the effect of time and operating conditions on a barrier’s lifetime. As part of this project, 3 full-scale crash tests and over 180 numerical simulations were carried out. The results allow for developing recommendations to improve planning, design and maintenance of road safety equipment, as well as for drawing up guidelines for optimal management of road safety infrastructure and for the insurance cover against collisions involving road safety devices.
Using numerical simulations, various types of road barriers were tested, e.g. steel w-beam guardrail barriers, cable barriers, concrete barriers, as well as bridge barriers. The influence of road conditions and structural features of barriers on the functionality of safety systems was investigated. Support structures used on roads (e.g. lighting columns, gantries) were also analysed. To perform all the numerical simulations in both projects, LS-DYNA was used. Examples of conducted simulations are shown in Fig. 1. Previous results can be viewed in papers [3-10,16,17,20-22].

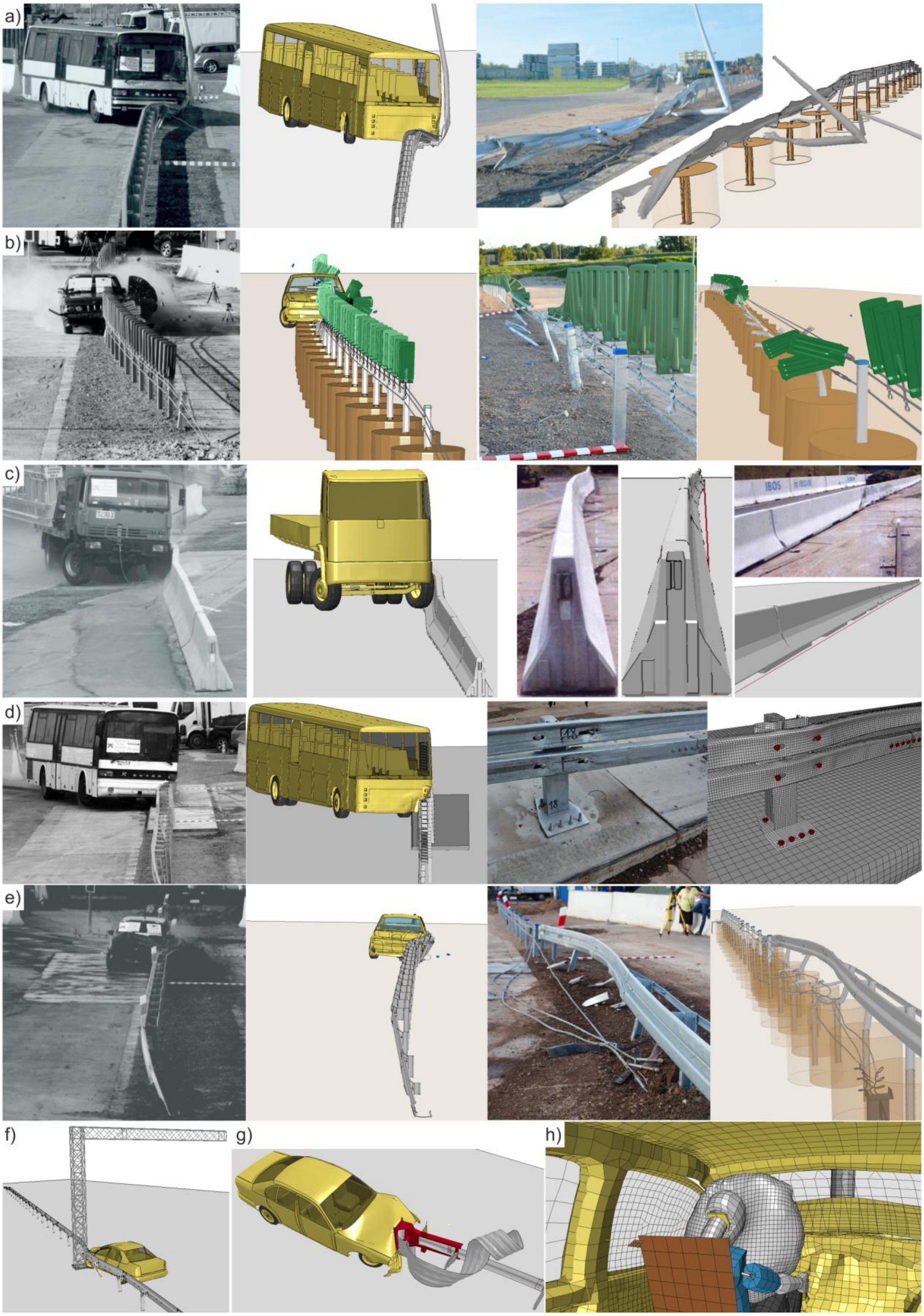

Fig.1: Examples of simulations in RID 3A and RID 3B projects: a) TB51 test with lighting columns within working width, b) TB32 test, c) concrete barrier TB41, d) bridge barrier TB51, e) transition – cable and steel barrier TB32, f) steel barrier TB32 with gantry, g) guardrail end terminal, h) dummy inside Geo Metro car hitting obstacle.

3 Background of the research

EN 1317 standard [11] describes the conditions for crash tests which are performed on safety barriers to allow for their usage on roads (Fig. 2). The choice of the tests depends on the desired containment level, e.g. to certify N2 level barrier TB32 and TB11 tests must be conducted. In the tests, the following performance levels are determined: working width and impact severity level.
Even though a standard test list is a reasonable representation of common road accidents, it may happen that the system can be hit by a different vehicle and under different conditions (angle, velocity) than during the obligatory crash tests. Among others, impacts of heavy goods vehicles can be especially dangerous, e.g. when a barrier placed on a median fail to contain the vehicle and it can invade the opposite lane (cross median crashes – CMC).
An additional phenomenon that accompanies such impacts is significant degradation of the top ground layer – a heavy vehicle driving into the median damages the soil under its wheels. In some situations, the return of the vehicle back onto the travelled lane after redirection may be difficult or impossible because the wheels meet the road structure and cannot drive back onto the road. These situations are displayed in Fig. 3.

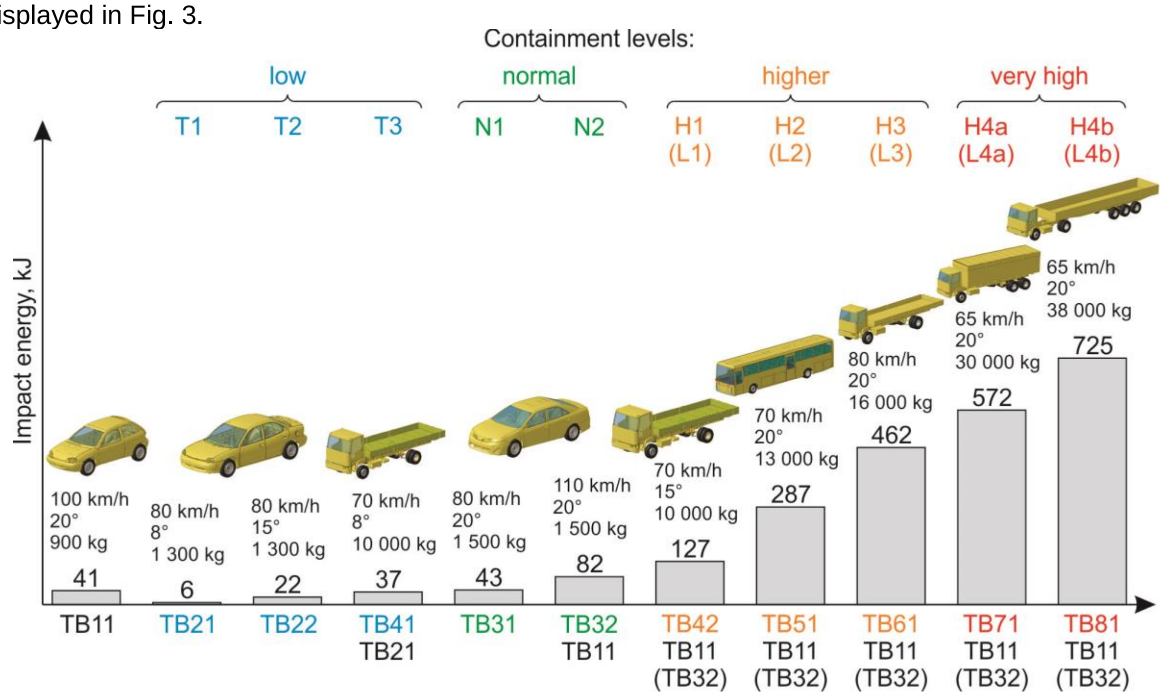

Fig.2: Summary of containment levels, crash tests and impact energy.

Fig.3: Examples of accidents involving HGVs. (source: General Director for National Roads and Motorways – GDDKiA, Poland)

In this work, due to the aforementioned issues, it was decided to carry out numerical simulations of heavy goods vehicles impacts into a cable barrier under conditions different from those assumed in EN 1317 standard [11]. The considered barrier system was originally tested at two containment levels: N2W4A (TB32 and TB11 tests) and L1W4A (TB42 and TB11 tests). In addition, the barrier was tested in the modified TB32 test – the results are presented in section 4.2.2. The aim of this work is to examine the effectiveness of the barrier during collisions with the 38t articulated HGV vehicle. An additional issue is studying the influence of the ground degradation caused by wheels on collision effects and the vehicle trajectory.

4 Numerical model

4.1 Vehicle

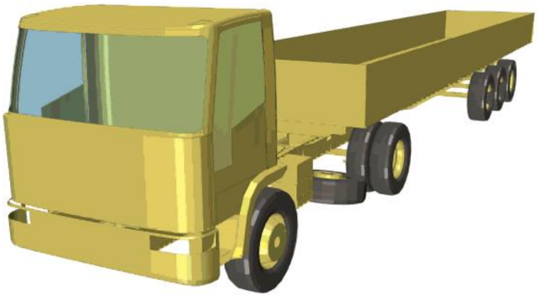

Fig.4: Vehicle (general view).

The vehicle numerical model used in this paper was downloaded from public NCAC repository [15] and is depicted in Fig. 4. It is a numerical representation of an articulated Heavy Goods Vehicle weighing approx. 38 tons. The vehicle consists of a tractor unit with two axles and a semi-trailer with three axles. The tractor unit's front is made up of a simple cab, a bumper, wheel arches and an engine. The semi-trailer is attached near the truck's rear axle. The vehicle has a total of 12 tires (excluding a spare tire mounted on the frame), 6 of them attached to the unit and 6 attached to the trailer. All of them have the initial pressure set at 0.6 MPa. The trailer is loaded using nodal point masses weighing 26690 kg. The FE model is composed of 57680 nodes which comprises 51181 shell elements, 2508 solids, 86 beams and 69 discrete elements. Most of the constitutive relations are represented using the piecewise linear plasticity material law [13,14]. The shell elements are calculated using the fully integrated Belytschko-Tsay formulation [13,14]. Depending on the solid elements' location, different formulations were used. Solid FE formulations in the model vary from those with constant stress across the volume, to those with fully integrated selectively reduced and those fully integrated with nodal rotations [13,14].
The vehicle's tractor unit is 2.82 m high and 2.49 m wide. The overall length of the truck with the trailer equals 16.16 m. These and other important measurements are presented in Fig 5. The centre of gravity is marked with a red dot and calculated according to normative requirements [11]. A summary of the vehicle specifications is shown in Table 1. It can be noticed that the vehicle is 149.8 kg heavier than the normative 38t HGV weight found in the European Standards.

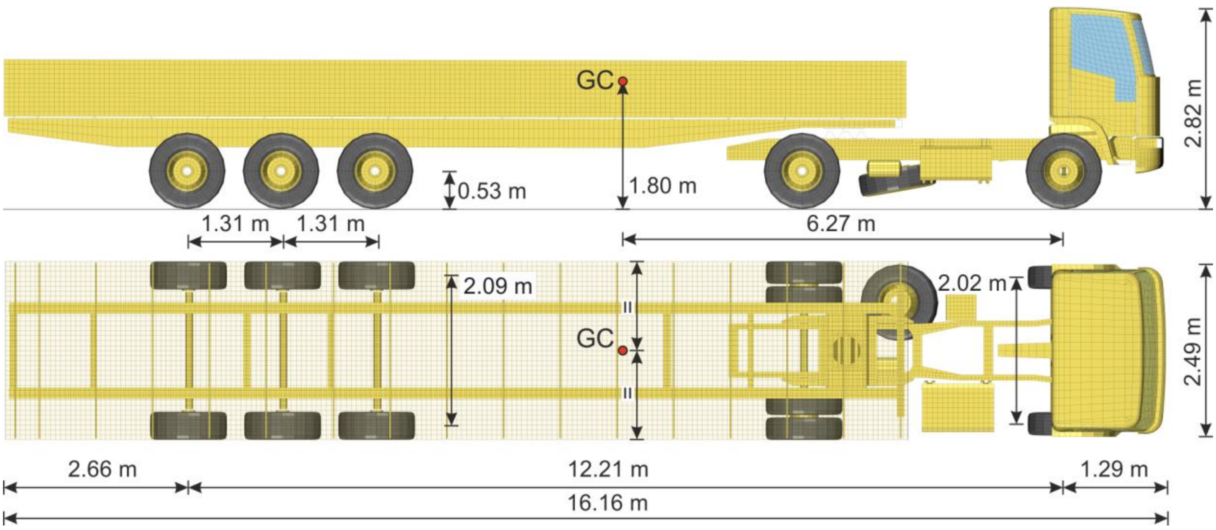

Fig.5: Articulated Heavy Goods Vehicle 38t dimensions.

	Model dimensions	EN 1317 requirements	Requirement fulfilment
Name	Articulated HGV 38t		–
Number of axles	1 steering axle + 4		–
Mass	39249.8 kg	38000±1100 kg	No
Length	16.16 m	n/a	–
Width	2.49 m	n/a	–
Centre of mass location	CG_X: 6.27 m CG_Y: 0.0 m CG_Z: 1.80 m	CG_X: 6.20 ± 0.62 m CG_Y: ± 0.10 m CG_Z: 1.90 (+ 0.29, - 0.10 m)	Yes Yes Yes
Wheel track (front and rear)	2.02 m – front 2.09 m – rear	2.00 ± 0.30 m	Yes Yes
Wheel radius (unloaded)	0.54 m	0.55 ± 0.08 m	Yes
Wheel base (between extreme axles)	12.21 m	11.25 ± 1.69 m	Yes
FEM details	57680 nodes 53844 FE	n/a	–

Table 1: Vehicle specifications.

4.2 Safety system

4.2.1 General description

A numerical model of the cable barrier was developed. The length of the whole system is 64.124 m, the height – 0.75 m. This safety system consists of three wire ropes attached to steel posts with hooks. The posts are embedded 0.95 m in the soil at the spacing of 2 m. The last two posts at each end of the barrier are equipped with additional plates, which helps to stabilize the posts in the ground. The height of the outermost posts is 0.55 m. On the top of each post, a cap is placed and these elements have no structural function. In the actual cable barrier, the ends of each wire rope are mounted onto massive concrete blocks buried in the ground. During the full-scale crash test, the motion of the block was not noticed and thus in the numerical model it was decided to use a simplification consisting in fixing the ends of the ropes. The numerical model of the barrier consists of 182333 nodes and 206064 finite elements. The details of the model are presented in Fig. 6. The most important details of the computational model and the parameters of the barrier's components are listed in Table 2. Fig. 7 shows 3 curves included in a material model of the wire ropes taken from [2,18,19]. A comparison of the numerical model and the barrier used in the crash test is displayed in Fig. 8.

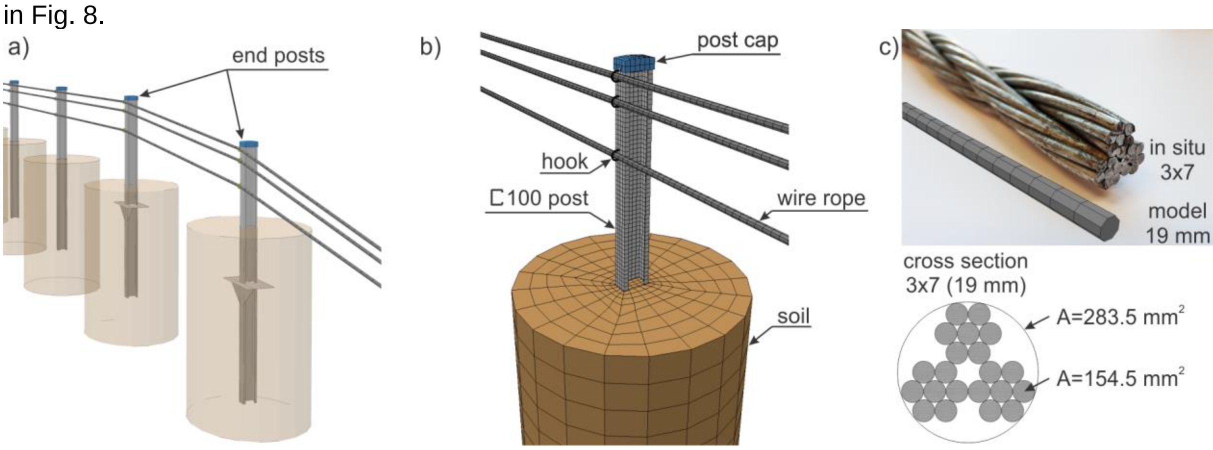

Fig.6: Details of computational model, a) end of barrier, b) system components, c) comparison of cable's numerical model and real wire rope.

Part	Technical data	Description
Wire rope	cross section 3x7 19 mm diameter	Beam elements – Belytschko-Schwer resultant beam (ELFORM=2) *MAT_MOMENT_CURVATURE_BEAM (*MAT_166) Properties taken from [2,18,19] Mass density 4308.5 kg/m^3; Young's modulus 62.8824 GPa; Poisson's ratio 0.3, EPFLG=1.0 Curves force-strain, bending moment-bending curvature, torque-rate of twist are shown in Fig. 7 (taken from [2,18,19])
Tensioning element	Between post no. 4 and 5 22.6 kN Force	Beam elements – discrete beam/cable (ELFORM=6) *MAT_CABLE_DISCRETE_BEAM (*MAT_071) Mass density 7948 kg/m^3; Young's modulus 205 GPa, Initial tensile force 22.6 kN
Post	C100 170 cm length 4 mm thickness	Shell elements – Belytschko-Tsay (ELFORM=2) *MAT_PIECEWISE_LINEAR_PLASTICITY (*MAT_024). Mass density 7950 kg/m^3; Young's modulus 205 GPa; Poisson's ratio 0.3; The stress-strain curve obtained from tensile test
Hook	5 mm diameter	Beam elements – Hughes-Liu with cross section integration (ELFORM=1) *MAT_PIECEWISE_LINEAR_PLASTICITY (*MAT_024). Mass density 7948 kg/m^3; Young's modulus 205 GPa; Poisson's ratio 0.3; The stress-strain curve taken from NCAC [15] *MAT_SPOTWELD (*MAT_100) – for the last beam element, effective plastic strain at failure (EFAIL) is 0.2. This solutions allows the cable to detach from post
Post cap	Mounted on the top of the posts, no structural function	Shell elements – Belytschko-Tsay (ELFORM=2) *MAT_RIGID (*MAT_020)
Soil	modelled as individual cylinders 133 cm height 80 cm diameter	Solid elements, constant stress solid element formulation (ELFORM=1) – straight section of the barrier Solid elements, 1 point tetrahedron (ELFORM=10) – the two post at the both end of the barrier *MAT_SOIL_AND_FOAM (*MAT_005), parameters taken from NCAC public library [15]

Table 2: Parameters of cable barrier system and details of computational model.

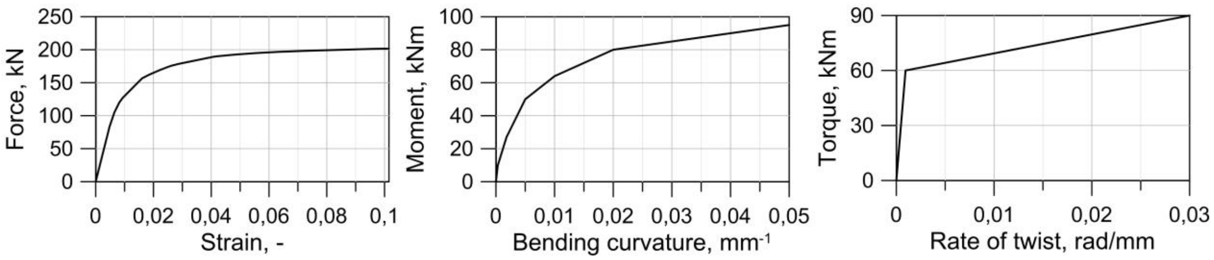

Fig.7: Curves implemented in the material model of wire ropes.

Fig.8: Full-scale structure (left) and its computational model (right).

4.2.2 Validation

The numerical model was subjected to a validation process based on test results from a full-scale crash test conducted in IBOS (Research Institute for Protective Systems, www.ibos.com.pl) in Inowrocław, Poland. It was a modified TB32 crash test (1500 kg, 110 km/h) in which the impact angle was changed from 20° to 7°. In the crash test and a numerical simulation, a BMW model was used. The computational model of the vehicle was developed by Transpolis (formerly LIER), the French crash-test house and digital simulation office for road safety equipment. A comparison of the results is presented in Table 3. A comparison of the damage and a snapshot of the impact is displayed in Fig. 9.

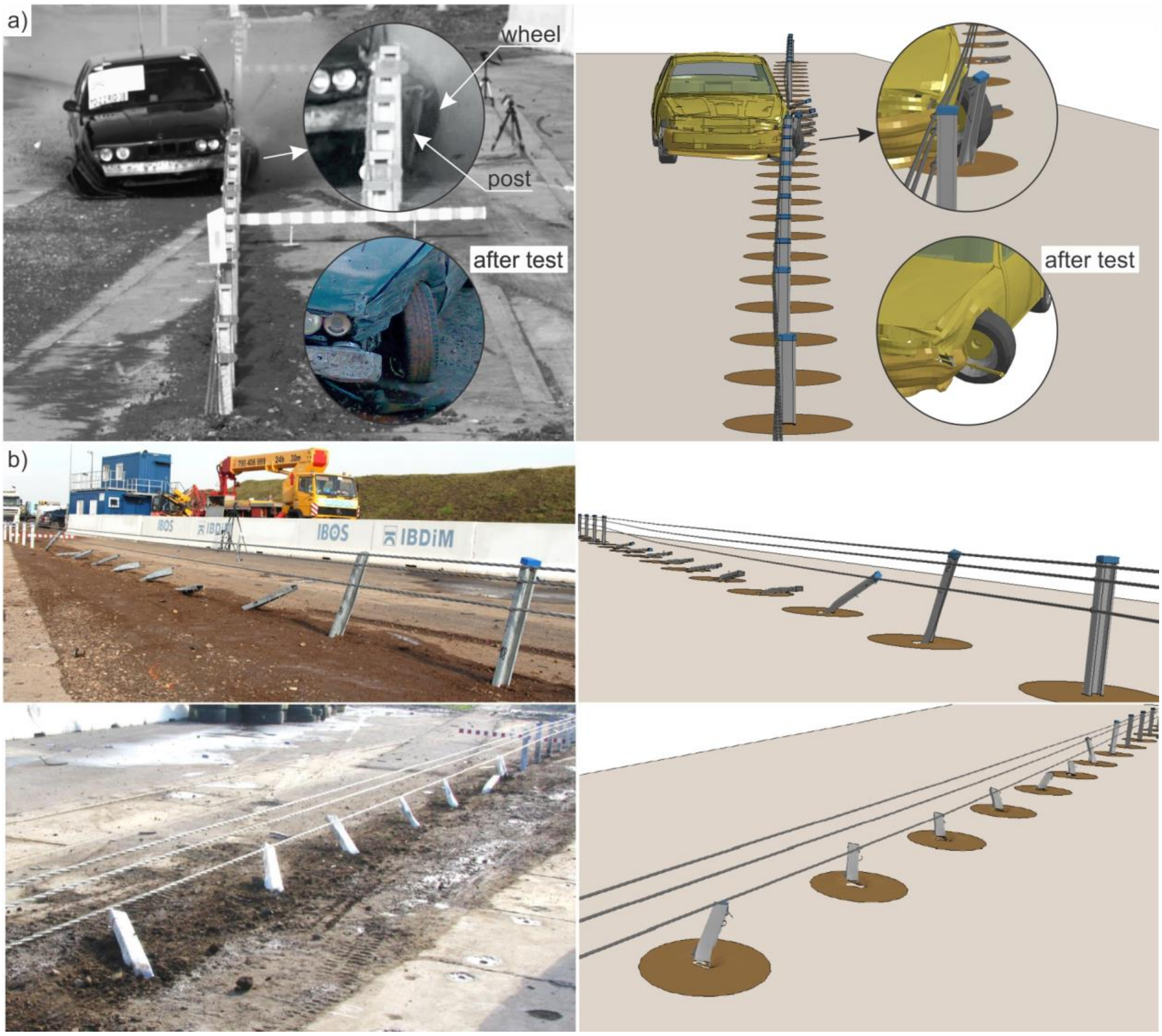

Fig.9: Comparison of numerical simulation (right) and crash test (left), a) general view, b) system deformation.

Indicator	Numerical simulation	Full-scale crash test
Working width W_M	0.65 m	0.55 m
Dynamic deflection D_M	0.50 m	0.52 m
ASI	0.38	0.35
THIV	15 km/h	16
THIV-X | THIV-Y	9.2 km/h | 11.7 km/h	8.4 km/h | 13.0 km/h
Time of flight of the theoretical head	0.24 s	0.21 s

Table 3: Comparison of numerical simulation and full-scale crash test results.

5 Numerical simulations

5.1.1 Impact analysis

The numerical model of the barrier was validated based on the results from the full-scale modified TB32 test. In the model, the BMW vehicle is replaced with an HGV and numerical tests were carried out.
The simulation tests parameters correspond to the TB81 test in which the articulated HGV impacts the barrier at the speed of 65 km/h. Numerical simulations were divided into two groups. The parameter that varied was the vehicle impact angle.
In the first group, the HGV vehicle hits the barrier of the same length as in the full-scale crash test. It is assumed that the ground on which the vehicle goes cannot deform. Fig. 10a illustrates this case. The impact angles from 2° to 20° are investigated.
In the second group, it is assumed that as a result of the HGV entry into the median, the ground degenerates. The vehicle damages the top 20 cm of the ground layer and strikes the barrier. After redirection by the barrier, the vehicle cannot return on the road because the wheels run into the road's structure as described in section 3. Hence, the expected contact length and the number of damaged posts is greater than in the tests from the first group. Therefore, it was decided to lengthen the barrier by 20 m. The damage of the ground is modelled by means of appropriate shaping of its surface, taking into account the 20 cm step, as shown in Fig. 10b. The impact angles from 2° to 10° are investigated.

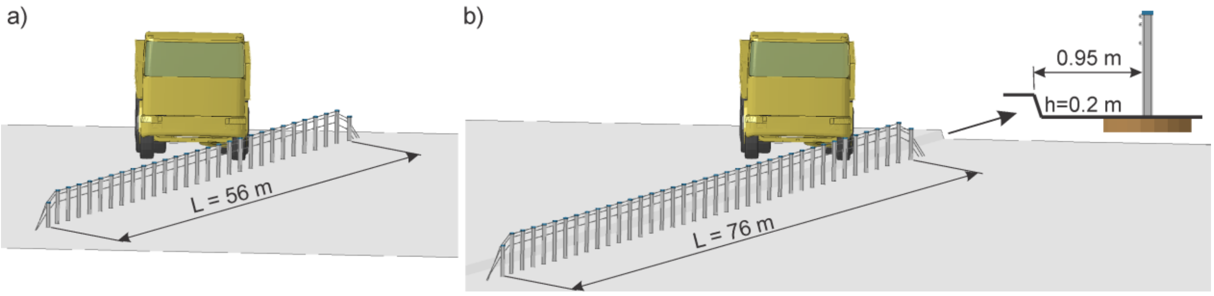

Fig.10: General views of analysed crash test, a) first group – even terrain, b) second group – ground degradation taken into account.

5.1.2 Results

The results of the numerical simulations involving the HGV and the cable barrier are shown in Table 4, where the test names represent mass (in tonnes) / impact velocity (km/h) / impact angle (degrees), respectively. The first seven tests present the simulation results for the first group, and the next four are for the second group, where the ground degradation is taken into account (letter “s” is added to the name of the test).
In Table 4 the following results are presented: working width (W_M) [11], dynamic deflection (D_M) [11], residual displacements of the barrier, the length of contact, the number of damaged post, information if the vehicle rolls over or goes through the barrier, the vehicle velocity and angle at the time of leaving the barrier. Here, the residual displacement of the barrier indicates the maximum lateral distance between the most outer part of the barrier and the vertical surface passing through the undeformed barrier’s face from the traffic side.
Generally, the vehicle hits the barrier, the barrier contains it and then enables the vehicle to go back on the road. As a result of the impact, the cables are detached from the posts, which are bent to the ground. Due to the impact, a significant number of posts are usually damaged.
For small impact angles, the dynamic deflection and working width are small and the vehicle dissipates a small amount of kinetic energy. Therefore, the velocity at the moment of leaving the barrier decreases insignificantly compared to the initial speed of 65 km/h. As the angle increases, the energy of the impact growths and thus the indicators W_M and D_M, the length of contact and the number of damaged posts increase. The only exception is the impact at a small 2° angle. Here, the length of contact is significant because the vehicle goes along the barrier and slightly pushes against it causing damage. The posts are not completely bent to the ground, as it happens in other cases, but are tilted from the vertical position. Therefore, the value of residual displacement is insignificant.
Based on the results, it can be concluded that in the case of soil degradation, HGV rolls over at a smaller impact angle (7°) than if the soil erosion is impossible (12°). The part that tilts and rolls over first is the trailer. As a result of soil degradation under the wheels, the indicators values describing the

barrier's deformation (W_M and D_M) are higher compared to the cases without the ground degradation. The same holds true for the contact length and number of damaged posts. It is worth noting that the length of the barrier damage for the second group is similar to the length of the barrier tested in the crash test. Therefore, the extension of the barrier by 20 m for these cases is justified.
In the cases considering soil degradation, the HGV leans and pushes against the barrier more than in the corresponding cases without degradation. This results in greater forces in the cables, as shown Fig. 11. The impact angle of 7 degrees is a borderline case where, with the assumption of 20 cm soil degradation, the vehicle rolls over – see Fig. 12. Nonetheless, the cable forces are much below the load-carrying capacity, which is approx. 200 kN.
The residual displacements for the analysed impacts do not exceed 1.0 m. This value is determined by the post which is bent to the ground. The undamaged post is 0.75 m in height.
Fig. 13 shows the results of 38/65/07/s virtual test compared to a real road accident. In both cases the trailer overturns and overlaps the barrier while the truck remains on the traffic side.

test	W_M, m	D_M, m	Disp. m	Contact length, m	Dam. Posts, pcs	Vehicle rollover	Vehicle break through	Leaving	
								Angle, °	Speed, km/h
38/65/02	0.29	0.17	0.23	40	20	No	No	0.3	62.9
38/65/05	0.70	0.23	0.61	12.5	6	No	No	3.8	61.9
38/65/07	0.82	0.45	0.78	12.5	7	No	No	6.2	59.4
38/65/10	0.84	0.78	0.80	20	10	No	No	2.8	55.4
38/65/12	0.90	0.88	0.79	32.9	17	Yes	No	-	-
38/65/15	1.24	1.22	0.82	32.1	22	Yes	No	-	-
38/65/20	1.73	1.71	0.76	38	22	Yes	No	-	-
38/65/02/s	0.87	0.25	0.73	56.5	13	No	No	0.3	62.3
38/65/05/s	0.96	0.62	0.82	44	20	No	No	0.4	51.4
38/65/07/s	1.03	1.00	0.99	51.8	28	Yes	No	-	-
38/65/10/s	1.03	0.92	1.01	51.5	26	Yes	No	-	-

Table 4: Numerical simulations results.

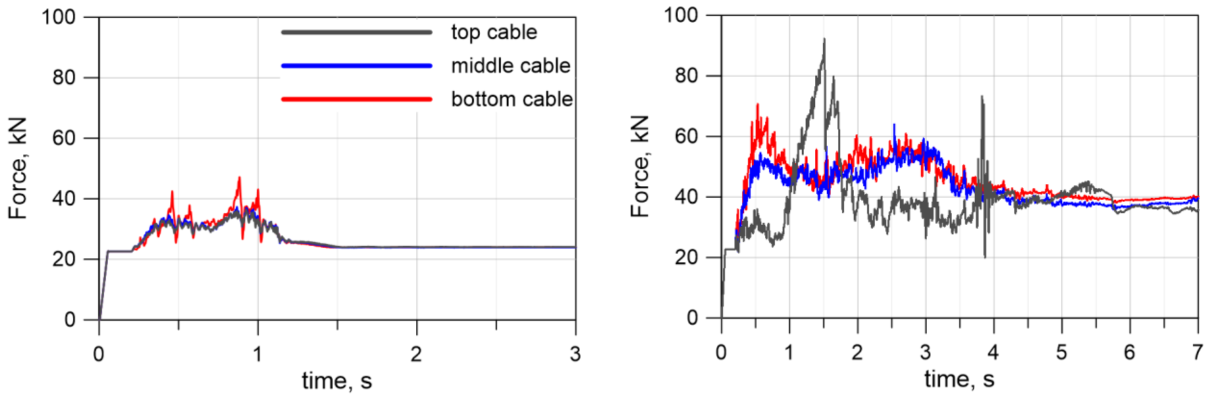

Fig.11: Forces in cables during 7° impact - simulations 38/65/07 (left) and 38/65/07/s (right).

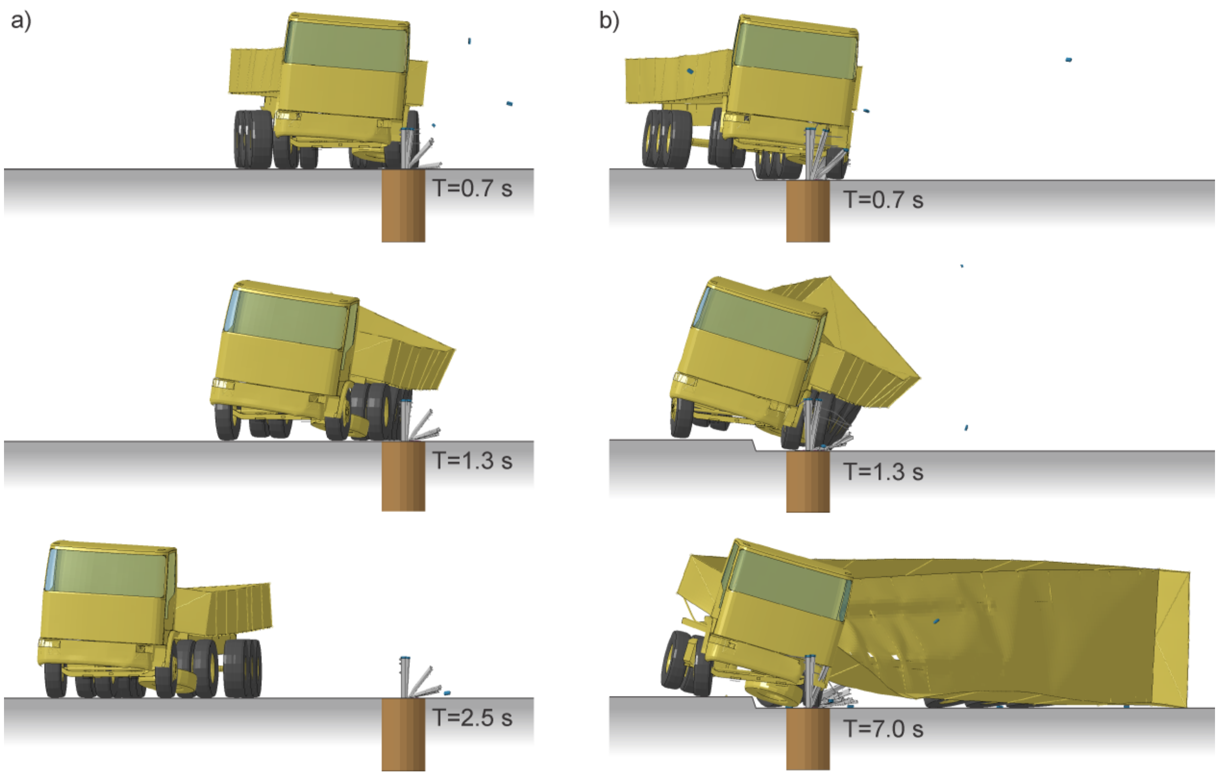

Fig.12: Comparison of vehicle trajectories during 7° impact, a) 38/65/07 simulation, b) 38/65/07/s simulation.

Fig.13: Comparison of numerical simulation 38/65/07/s (right) and a real road accident (left). (photo source: General Director for National Roads and Motorways – GDDKiA, Poland)

6 Conclusions

LS-DYNA is commonly used to perform numerical simulations of crash tests. The virtual tests allowed for reliable analyses of many cases, also including those not covered by crash test standards. Numerous scientific papers prove their usefulness, e.g. [1, 12]. LS-DYNA was successfully employed for the purposes of the RID 3A and RID 3B projects aimed at comprehensive studies of road safety equipment.

In this paper, it was decided to use the numerical model of a cable barrier which passed the validation process, and on the basis of this model to examine various scenarios of Heavy Goods Vehicle impact. These collisions, due to an HGV mass, usually trigger major damage to the barrier, greater than in the case of passenger vehicles. Therefore, the risk of breaking through the safety barrier is significantly higher.

This study set out to examine the influence of the impact angle and soil degradation under the wheels on the result of the crash. The research revealed that both of the above factors affect the outcome of the impact. An impact at a larger angle can result in the vehicle rollover with the trailer overturned. Soil degradation makes it difficult for the vehicle to leave the barrier which results in increased barrier damage length. Numerical simulations using LS-DYNA allow for a unique insight into the mechanisms occurring during this kind of crash event.

Acknowledgements

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